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COMPARATIVE ANALYSIS OF LEADING AND LAGGING LEFT TURNS

Final Report

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16. Abstract <p>This project was undertaken to compare operational and safety characteristics of leading verses lagging protected left turn operation. The measures of effectiveness included field measured intersection delay with leading and with lagging left turns. Intersections in Pima County, Glendale, Tempe and Mesa, Arizona were studied with both leading and lagging operation. Intersection delay studies were also done with first car verses third car actuation of leading protected left turn phases. Signal progression was studied with leading, lagging and combination of leading and lagging left turns which provided the best progression. This evaluation was accomplished with an instrumented vehicle and travel time runs throughout a grid.</p> <p>Accident studies were conducted in Tucson, Pima County and Scottsdale, Arizona. These studies compared accident frequency before and after the conversion from leading to lagging left turns.</p> <p>A public opinion survey was conducted to obtain motorists' preference of leading or lagging left turns.</p>			
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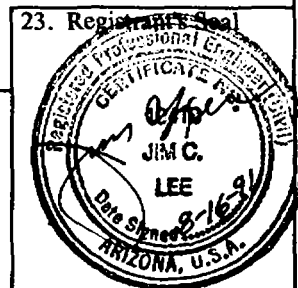


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EXECUTIVE SUMMARY

COMPARATIVE ANALYSIS OF LEADING AND LAGGING LEFT TURNS

INTRODUCTION

In 1985, the City of Tucson initiated an effort to convert the protected left turn signal phases from a leading to lagging operation. It was believed that the use of lagging left turns would improve intersection operations and network flows. The limited studies following the conversion from leading to lagging left turn operations suggested that operational and safety advantages were realized.

Pima County has a number of signalized intersections in proximity to the City of Tucson. In order to provide uniformity in the area, Pima County converted from leading to lagging left turn operations in 1987.

Based on the reported Tucson experience, other jurisdictions in Arizona began to consider changing to the lagging left turn phasing. Scottsdale, which is in the Phoenix metropolitan area, converted their protected left turn phasing to a lagging operation in early 1989.

The evaluation studies by the City of Tucson were rather limited, and there were a number of questions about the operational and safety aspects of the protected left turn phasing alternatives. In an effort to address these questions, a research project was initiated in 1989 by the Arizona Department of Transportation for the purpose of comparing the leading and lagging left turn operations. More specifically, the study was to investigate the following four basic research questions:

- 1) Is there a difference in intersection delay at isolated intersections between the leading and lagging left turn operation?
- 2) Is there a difference in signal progression among leading only, lagging only, and mixed left turn operations?
- 3) Is there a difference in accident experience between leading and lagging left turn operations?
- 4) Is there a motorist preference between leading and lagging operation?

FIELD STUDIES AND ANALYSIS

In order to address the research questions, field studies were undertaken in the Phoenix and Tucson metropolitan areas. The Phoenix area portion of the research focused primarily on the effects of the various left turn phasing patterns on signal coordination and system behavior. Also, the Phoenix area research evaluated the effects of left turn phasing on intersection delay and accidents. Finally, a public opinion poll was performed to obtain information regarding possible motorist preferences for the leading or lagging left turn phasing.

The Tucson area portion of the research project examined the accident experience resulting from the conversion of left turn operations at intersections in the City of Tucson and Pima County. In addition, the study compared traffic operations before and after the left turn conversion at selected isolated signalized intersections in Pima County.

Accident Studies

The City of Scottsdale, in 1988, undertook a six month trial period of lagging left turn operation. Five intersections were converted from leading to lagging operations in June 1988. Based on the trial period experience, the City of Scottsdale converted an additional 45 signals to a lagging operation in the early part of 1989. Due to the brief history of the use of lagging left turns, it was necessary to compare a one year accident experience with the lagging left turns with three years of accident experience with the leading left turns. It is recognized that a multiple year after period would be more desirable due to the random nature of accidents and the multitude of factors which may influence accident patterns. For this reason, the statistical test which was used in the analysis makes use of a control group that serves to discount the influence of extraneous factors and helps to identify general trends in accidents. Of the 50 intersections in the City of Scottsdale that were converted from leading to lagging left turns, nine intersections were selected for the accident study. The accident experience during the before and after periods were compared with a control group consisting of two phase signalized intersections in the City of Scottsdale.

The conversion from leading to lagging left turn operation at signalized intersections under the control of Pima County occurred in 1987. While 37 intersections were involved in the conversion program, some of the intersections were not suitable for accident analysis due to other changes; thus only 21 of the intersections were included. Because some of the approaches at these intersections did not have protected left turn movements, the accident analysis was accomplished by approach. In this way, only the approaches that were affected by the conversion from leading to lagging left turns were analyzed. The analysis period consisted of two years prior to the conversion of the signal operations and approximately two years following the change over. At a few intersections, the duration of the before period was less than two years due to the date of signal installation. A "before and after" analysis technique was used where the accident experience at each intersection approach was compared.

In the City of Tucson, the conversion from leading to lagging left turns was accomplished in 1985. Again, a "before and after" comparison of the accident experience at individual intersections was undertaken. Data for a before period from 1982 to 1984 and an after period from 1986 to 1987 were provided by the City from computerized accident reports. A total of 62 intersections were included in the analysis of which 50 were the intersection of major arterial streets. The remaining 12 intersections involved the intersection of major arterial streets with collector streets.

Travel Time Studies

In an effort to assess the effect of the left turn phasing alternatives on a system of signalized intersections, travel time studies were conducted in three cities in the Phoenix area. Alternative left turn phasing patterns were tested using travel time data along five routes in Glendale and four routes in Tempe. Four Glendale intersections and two Tempe intersections were changed from leading to lagging operation. The patterns tested were a) all leading left turns, b) all lagging left turns, and c)

a combination of leading or lagging left turns depending on which best fit the progression along the route. In addition, a combination phasing was tested along one route in Mesa.

In order to obtain a true comparison between leading and lagging left turns, it was necessary to use signal timing patterns developed by a common optimization program. Because of the ease of operation and the numerous runs that would be required as part of the combination portion of the study, the computer program known as FORCAST was utilized to determine the optimal signal timings.

Intersection Studies

Intersection stopped time delay studies were conducted at six Phoenix area locations to perform a comparative analysis of leading and lagging left turn operations. Manual stopped time delay studies were conducted at each intersection prior to changing from leading to lagging left turns. Five of the six intersections operated with protected/permissive left turn phasing on all approaches. The sixth intersection operated with protected only left turns on the northbound and southbound approaches and protected/permissive left turn phasing on the other two approaches. In addition, studies comparing leading left turns with a combination leading/lagging operation were conducted at one intersection in Mesa.

At some intersections in the Phoenix area, third car actuation is used on approaches with protected/permitted left turns. With this operation, the protected left turn phase will not occur unless three or more vehicles are queued in the left turn lane. As part of the research project, delay studies were undertaken for the purpose of comparing the third car verses the first car actuation. This particular part of the research evaluated only the leading left turn condition.

Prior to the conversion from the leading to lagging left turn operation, a limited number of intersections under the control of Pima County were selected for a "before and after" comparison of the effect of the change. Nine intersections were filmed with two time-lapse cameras from approximately 3:00 p.m. to 6:00 p.m. Following the change to lagging left turns, the intersections were again filmed during the same time periods. Due to difficulties at two intersections, only seven were included in the final detailed analysis. Using the film record of the intersections, data which represented pertinent operational parameters were extracted. For example, the measures included cycle length, stopped delay, and volumes.

In contrast to the intersections in the Phoenix area, all of the Pima County intersections were isolated and operating with actuated control. Because the intersections were in the outlying areas of Tucson, the traffic volumes were not equally distributed in terms of the opposing movements. There were very few cycles in which the approaching traffic failed to clear the intersection; thus the intersections were generally not operating at saturated conditions.

RESULTS AND CONCLUSIONS

Based on the field studies, it was found that intersection delay is significantly greater with the lagging left turn operation. No significant change in total delay was found with third car actuation of leading protected left turns. In addition, no significant differences were found in progression between the leading, lagging, and mixed operations. In terms of the accident experience, no significant

differences were found between the leading and lagging left turns. Finally, there was a mixed response from the motorist preference survey. Glendale drivers felt that leading left turns were better while Tempe drivers preferred the lagging left turns.

More specifically, the following results were found with respect to each of the questions posed for the research project:

1. *Is there a difference in intersection delay at isolated intersections between the leading and lagging left turn operation?*

The results of this study indicate significantly greater delay per approach vehicle occurs with lagging operation than with leading operation for the intersections and time period tested. It is important to note that the time periods tested were generally PM peak hour conditions. These would not be as likely to have sufficiently low left turn and through volumes to eliminate many protected left turn phases in the lagging condition. It is conceivable that in off peak conditions more of the left turns could be made in a permissive manner therefore skipping the protected left turn phase. Eliminating the protected phases would likely reduce intersection delay.

Intersection delay was also collected for test intersections with both first car and third car actuation. Although there was no significant difference between the two, this test also was only done in the PM peak hour condition. The probable benefit of third car actuation on intersection delay is most likely in off peak conditions.

2. *Is there a difference in signal progression among leading only, lagging only, and mixed left turn operations?*

There were no statistically significant differences in stops, delay or travel time with the different operating conditions. Additionally, the large number of signal timing optimization runs required to evaluate all combinations of leading and lagging operation makes for a cumbersome, time consuming process. The requirement that the Glendale and Tempe "mixed" operation was limited to either both leading or both lagging on the same street in order to avoid the "trap" restricted potential progression benefit. An additional limitation was that only four of eight multi-phase Glendale intersections and two of four multi-phase Tempe intersections were considered for change to lagging.

The most promise for benefit from lagging or mixed operation was found in the Mesa study where leading left turn operation was utilized for eastbound traffic and lagging for westbound traffic in the after condition. This was the operation which provided the best east-west progression. This mixed operation was possible without the trap condition because of the use of protected only left turns.

3. *Is there a difference in accident experience between leading and lagging left turn operations?*

In all three accident studies - Tucson, Pima County and Scottsdale, there was no significant difference in left turn accident history between leading and lagging operation.

4. *Is there a motorist preference between leading and lagging operation?*

Lagging left turns seem to be more favorably received in Tempe than in Glendale. This could possibly be due to the close proximity of Tempe to Scottsdale, where lagging left turns are utilized.

Public Perception Results

More Green Lights With:

	<u>Glendale</u>	<u>Tempe</u>
Leading	38%	30%
Lagging	16%	21%
Combination	24%	27%
No Difference/No Response	22%	22%

Left Turns Better With:

Leading	49%	30%
Lagging	42%	61%
No Difference/No Response	9%	10%

The field studies by the research team provided valuable insight to the understanding of the many variables which influence left turn operations. Within the scope of this study and the conditions at the study sites, it was not possible to collect data for all combinations of the pertinent variables. The results of the field studies together with a somewhat theoretical analysis or understanding yield a comprehensive assessment of leading and lagging left turn operations. In essence, a number of variables have an impact on the effectiveness of left turn alternatives at a specific site. The variables that should be considered fall into the general categories of a) signal control, b) network considerations, c) traffic characteristics, and d) driver perception.

PART I

INTRODUCTION

PART I presents an introduction to the research report, documents the literature search and discusses the research problem statement.

CHAPTER 1 gives a background to the consideration and use of a leading or lagging left turn operation. A brief summary of the research results is presented. The overall organization of the research report is also discussed.

CHAPTER 2 documents the findings of the literature search, summarizes the theoretical basis for using a leading or lagging operation and reviews actual experience with both operations. The research problem statement is presented which was used as the framework for carrying out the individual research studies. The following four research questions were addressed in the individual studies:

- Is there a difference in intersection delay at isolated intersections between leading and lagging operation?*
- Is there a difference in signal progression among leading only, lagging only and mixed operation?*
- Is there a difference in accident experience between leading and lagging operation?*
- Is there a motorist preference between leading and lagging operation?*

CHAPTER 1

INTRODUCTION

This research project entitled "Comparative Analysis of Leading and Lagging Left Turns" was conducted by Lee Engineering, Inc. in association with Dr. Robert H. Wortman. The rationale for this association in undertaking the research is based on the ability of Lee Engineering to conduct field studies in the Phoenix area while Dr. Wortman had information and data related to conditions in the Tucson area. The combined efforts of the two groups permitted a comprehensive investigation of the problem.

Lee Engineering was responsible for data collection and analyses of intersections in the Phoenix area, and Robert Wortman conducted the work related to analyzing intersections in the Tucson area. Following the accomplishment of these studies, the research team jointly evaluated the collective findings of the research and prepared this final project report.

Probably the most controversial item in the Arizona traffic engineering community for the last few years relates to leading versus lagging left turns. In 1985, the City of Tucson, Arizona initiated an effort to convert the protected left turn signal phases from a leading to lagging operation. It was believed that the use of lagging left turns would improve intersection operations and network flows. The limited studies following the conversion from leading to lagging left turn operations suggested that operational and safety advantages were realized.

Pima County has a number of signalized intersections in proximity to the City of Tucson. In order to provide uniformity in the area, Pima County converted from leading to lagging left turn operations in 1987. Based on the Tucson experience, other jurisdictions in Arizona began to consider changing to the lagging left turn phasing. Scottsdale, which is in the Phoenix metropolitan area, in early 1989 converted their protected left turn phasing to a lagging operation. There are widespread opinions as to the benefits of each of the two methods. A tremendous amount of misinformation and misunderstood information exists. This is particularly critical when one realizes the significant actions which are being taken and considered by cities and counties within the state based on this suspect information.

It should be noted that most intersections in Arizona with a protected left turn phase also have a permitted phase which allows motorists to turn left through gaps in opposing traffic. At intersections with permitted/protected phasing, simultaneous lagging left turn arrows are used to avoid trapping motorists who have pulled into the intersection while waiting to turn.

If more complete information regarding leading and lagging left turns is available and traffic operations decisions are based on that information, the opportunity exists for reduction in automobile delay and number of stops as well as increased safety. Certainly these are worthwhile goals. The need is further enhanced when one considers the reduction in auto emissions and fuel consumption associated with such operational improvements. This research project is intended to provide additional information in this area.

One of the perceived advantages of lagging left turns in a permissive/protected operation is the possibility of eliminating some of the protected left turn phases. This would occur when the left turning vehicles find sufficient gaps during the permissive period to reduce the protected green time or skip the phase.

Third car detection has been utilized by some Arizona cities to attempt to accomplish the same omission of the protected phase in a protected/permissive (leading) operation. This technique requires a vehicle actuation of a detector placed a distance back from the stop line where the third left turning vehicle would be stopped. The protected left turn phase only is called when this "third car detector" is actuated.

It is appropriate that a study be undertaken to provide a factual basis for making the determination of the type of left turn phasing needed at individual intersections within Arizona cities. Some of the questions addressed in this study include the following:

1. *Does lagging left turn operation reduce intersection delay?*

In other experiments documented in the literature based both on measured and simulated experiments, there generally has been found no significant difference in intersection delay between the two phase set options at isolated intersections.

2. *Does lagging left turn operation provide better signal progression?*

This study investigates the difference in number of stops and travel time along arterial streets with both leading and lagging operation.

3. *Is it necessary or desirable to have consistent phasing (either leading or lagging left turns) within any given city, urbanized area, and throughout the state of Arizona?*

There has been a concern among Arizona traffic engineers, elected officials and citizens that the mixture of leading and lagging operation among jurisdictions created safety or operational problems for motorists.

4. *What is the effect on accidents of leading versus lagging left turns?*

Although the City of Tucson has reported a reduction in accident rate with lagging left turn operation, it was based on only six months of after period. The Federal Highway Administration (5, p.17) reports a higher accident rate for lagging than leading left turn operation. This may be due to the previously discussed safety problem of phase overlap on permissive/protected operation.

5. *What is the motorists' perception of the leading versus lagging left turns?*

Based on the experience reported by Tucson (2) and Scottsdale (6) there may be a motorist preference of lagging over leading operation.

RESEARCH APPROACH

This research project was divided into several subareas for analysis as follows:

- Effect of leading vs. lagging left turns on intersection delay.
- Effect of leading vs. lagging left turns on signal system progression.
- Effect of leading vs. lagging left turns on accident experience.
- Effect of third car detection actuation on intersection delay.
- Motorists preference of leading and lagging left turns.

Intersection Delay

The intersection delay study was conducted both in the Phoenix area and in Pima County. At seven intersections in Glendale, Tempe and Mesa, the intersection delay with leading left turns was compared to that with lagging left turns. At the one Mesa intersection the only after condition involved a leading left turn in one direction and a lagging left turn in the opposing direction. The delay in the Phoenix area was obtained by counting the queued vehicles at 15 second increments. The Pima County intersection delay was obtained using time lapse photography with both leading and lagging left turns at 9 locations.

Signal System Progression

The signal system progression was evaluated in Glendale, Tempe and Mesa by driving an instrumented test vehicle down each street to be evaluated for six runs in each direction. The runs were conducted for each of four conditions in Glendale and Tempe:

- Existing timing (all leading).
- Optimized all leading timing.
- Optimized all lagging timing.
- Optimized combination.

It should be mentioned that all-lagging phasing was implemented only at the four Glendale intersections and the two Tempe intersections being changed although there were more intersections being timed and evaluated which were held to leading operation.

The combination timing consisted of the best combination (from a system signal progression standpoint) of leading and lagging left turns at the four Glendale and the two Tempe intersections being changed. The theory behind this test is that one can establish the best two-way progression on three streets of a grid by fitting the east-west green into the already established north-south red. This can also be done for the third street, however when attempting to "close" the grid, frequently the bands don't properly fit. It was hypothesized that having the flexibility on one of the streets would better permit a good grid closure.

The signal progression evaluation in Mesa consisted of the following:

- Existing leading operation.
- Combination of leading left eastbound and lagging left westbound.

This combination of leading and lagging left turns had been determined to provide better progression than all leading.

Accident Experience

A before (leading) - after (lagging) accident study was conducted in Tucson, Pima County, and Scottsdale. Although there were varying periods in both conditions among the three jurisdictions, Scottsdale generally had a shorter after period than the other two. This was because lagging left turn operation had been more recently implemented in Scottsdale.

Third Car Detection Evaluation

A study of intersection delay with first car versus third car detection was conducted at 3 intersections in Phoenix and 2 intersections in Tempe. The purpose of the evaluation was based on the premise that if only one or two vehicles were desiring to make a left turn, they could do so during the permissive green period or during the clearance interval. It was hypothesized that eliminating some of the protected left turn phases should provide more green time for through vehicles thereby reducing intersection delay.

It should be noted that one of the possible advantages of third car actuation is the ability to continue to have the phase overlap capabilities associated with protected/permissive (leading) operation.

Motorists' Preference

In an attempt to determine if there was a drivers' preference for either leading or lagging left turns, a questionnaire was sent out to owners of vehicles which had been observed driving on streets being tested in Glendale and Tempe. Approximately 4500 questionnaires were mailed with about half going to drivers in each of the two cities.

ADVISORY COMMITTEE

An important part of this study involved the formation and use of an advisory committee of municipal, county and state traffic engineers within the state. The philosophy was that these are the individuals who have to operate the signal systems, therefore they should be directly involved in

planning, conducting and evaluating the research operation. Advisory Committee Members are as follows:

<u>Representative</u>	<u>Agency</u>
Roger Hatton	ADOT Traffic Engineering Section
Robert Pike	ADOT Research
Al Letzkus	Maricopa County
Paul Basha	City of Scottsdale
Kenneth Shackman	Pima County DOT
Hugo Malanga	City of Glendale
James Matteson	City of Phoenix
Richard Nassi	City of Tucson
Ron Krosting	City of Mesa
Harvey Friedson	City of Tempe

ORGANIZATION OF REPORT

This research report is organized into five parts. Part I presents an introduction to the research, a summary of the literature search and discussion of the research problem statement. Part II presents the accident studies which were carried out in the City of Scottsdale, Pima County and the City of Tucson. Part III presents the results of traffic operations studies which were conducted in the Phoenix area and Pima County. Part IV presents the results of the public awareness and perception analysis conducted for the cities of Glendale and Tempe. Part V discusses the study results, theoretical analysis of leading and lagging left turns, and presents recommendations for future research work.

STUDY RESULTS

This research study yielded the following results:

- Lagging operation resulted in greater delay per approach vehicle than leading for the intersections and time periods tested.
- There was no significant difference in signal progression between all leading left turns, all lagging left turns and some streets with leading and some streets with lagging.
- Although not significant due to limited sample size, there was a notable reduction in delay and travel time on the one street tested with leading left one direction and lagging left in the opposing direction when compared to the leading condition in both directions.
- There was no significant difference in accident experience between leading and lagging operations.

- Motorists in Glendale and Tempe felt that they experienced more green lights with leading than lagging. Glendale motorists felt that left turns were better with leading operation while Tempe motorists felt left turns were better with lagging operation.

It should be noted that delay studies for leading/lagging and 3rd/1st car actuation were primarily conducted during the PM peak hour. It is possible that there might be a greater chance to skip protected left turn phases for both lagging and 3rd car actuation in an off-peak period.

CHAPTER 2

LITERATURE REVIEW

The concept of a lagging green left turn interval is not new. Neither is the question as to whether leading or lagging left turns is preferable as evidenced by the following excerpt from the 1965 version of the *Traffic Engineering Handbook* (1, p.403).

While not exactly a third phase, the use of a leading (advance) or lagging (delayed) green may be helpful in special situations.

At an intersection having a fairly heavy left-turn movement, say on Phase A eastbound, the holding of the westbound Phase A green for 5 to 10 sec after eastbound traffic receives its green could be helpful. This is known as giving a "leading" green to Phase A eastbound.

On the other hand, if near the end of Phase A, an additional 5 to 10 sec is allotted to Phase A eastbound, it would be receiving a "lagging" green.

The use of either one of these should be approached with extreme caution because a motorist who is receiving the shorter green might not realize it since he sees opposing traffic flowing freely. He may continue to proceed into the intersection against a red signal and may collide with a motorist making a left turn who expected that the opposing motorist would stop.

Some authorities feel that the leading green is probably less hazardous than the lagging green because motorists in opposing directions would generally be starting from a stopped position.

On the other hand, some authorities favor the lagging green because of a tendency for traffic standing at the Stop line in the opposing direction to start when they see the traffic having the leading green begin to move. They feel that the left-turn capacity is increased because the front left-turning vehicles have moved into the intersection during the regular green period and a greater number of vehicles are able to clear the intersection than when they are starting from the Stop line at the beginning of a leading green interval.

Potential for the lagging left turn being more hazardous as mentioned in the previous excerpt refers to what is sometimes called the "trap" of lagging left turns. When lagging left turns have been used with phase overlap (one left turn becomes lagging protected while the opposing permissive left turn terminates) an increase in accidents has been observed in some locations. The driver who is waiting in the intersection to turn left and sees all the traffic lights on the approach change to red and adjacent through traffic stop expects the opposing traffic to also be stopping. The driver waiting in the intersection to turn left either turns unknowingly into the path of opposing traffic which still has the green or gets trapped in the middle of the intersection. The phasing diagram on Figure 2-1 demonstrates how this situation could occur.

The potential problem occurs in transition from the 2-6 phase to the 2-5 phase. As the driver of the left turn permissive movement associated with phase 6 sees the yellow, he might erroneously assume phase 2 is also ending and pull out in front of phase 2 traffic still viewing a green indication.

One way to alleviate this problem where permissive lagging left turn operation is used, is to require the left turns in opposing directions to be operated simultaneously in a protected manner. This is undesirable where there is a definite imbalance in directional flow. Consider the example of considerably more left turn and through traffic in a northbound direction during a particular period of the day. If the northbound lefts cannot be accommodated during the permissive operation they

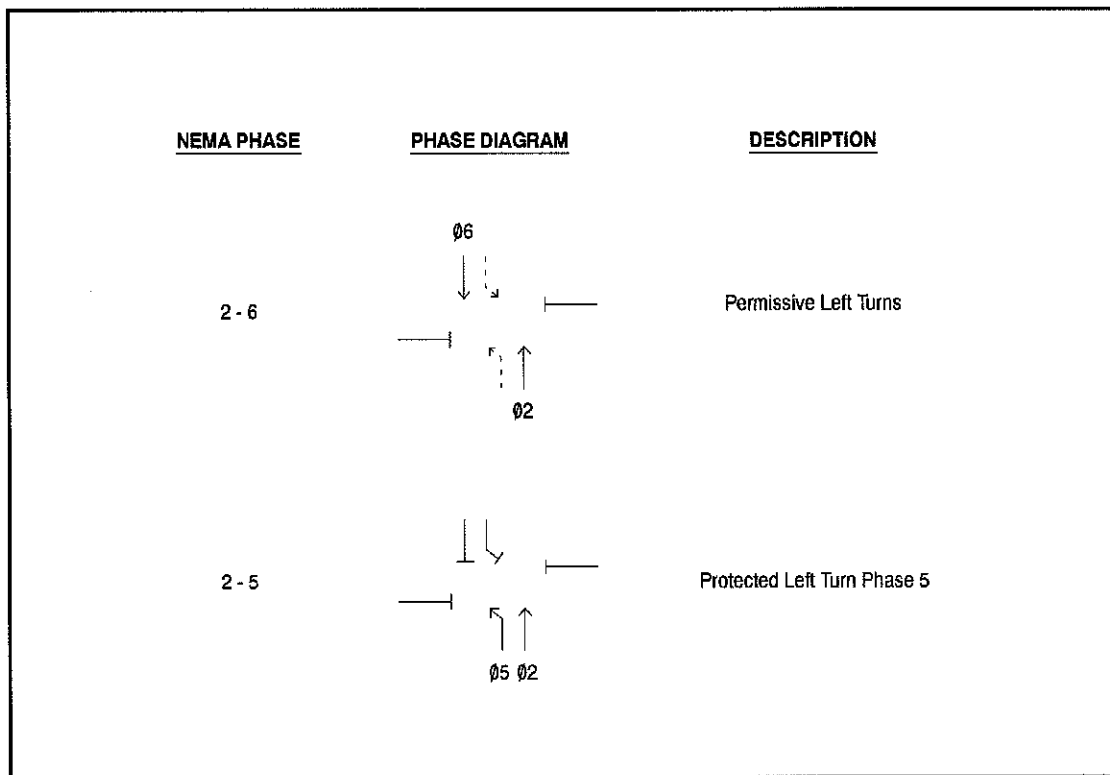


Figure 2-1. Potential Safety Problem: Lagging Left with Phase Overlap

will have to be accommodated in the protected phase. If there is little southbound left turning traffic, the heavy northbound through movement is unnecessarily delayed.

Another possibility is the use of protected only lagging left as shown in Figure 2-2. Although this loses the advantage of permissive operation, it gains the advantage of phase overlap.

In this situation there are no permissive left turning vehicles which would be expecting an opposing through termination. In this manner, where there is unbalanced flow and protected only operation, phase overlap can apparently be utilized without increased accident potential.

The simultaneous dual lag operation is utilized by the City of Tucson, which has the most experience within the state with operating lagging left turn operations. In 1984, Tucson conducted an experiment on 22nd Street from Tucson Blvd. to Kolb Road. In this study, by converting from leading to lagging operation they reported the following (2):

DELAY	-	45% reduction in off peak hours 40% reduction in peak hours
FUEL CONSUMPTION	-	reduction of 61 gallons per day per intersection
AUTO EMISSIONS	-	30% reduction in off peak hours 40% reduction in peak hours
ACCIDENT RATE	-	40% reduction

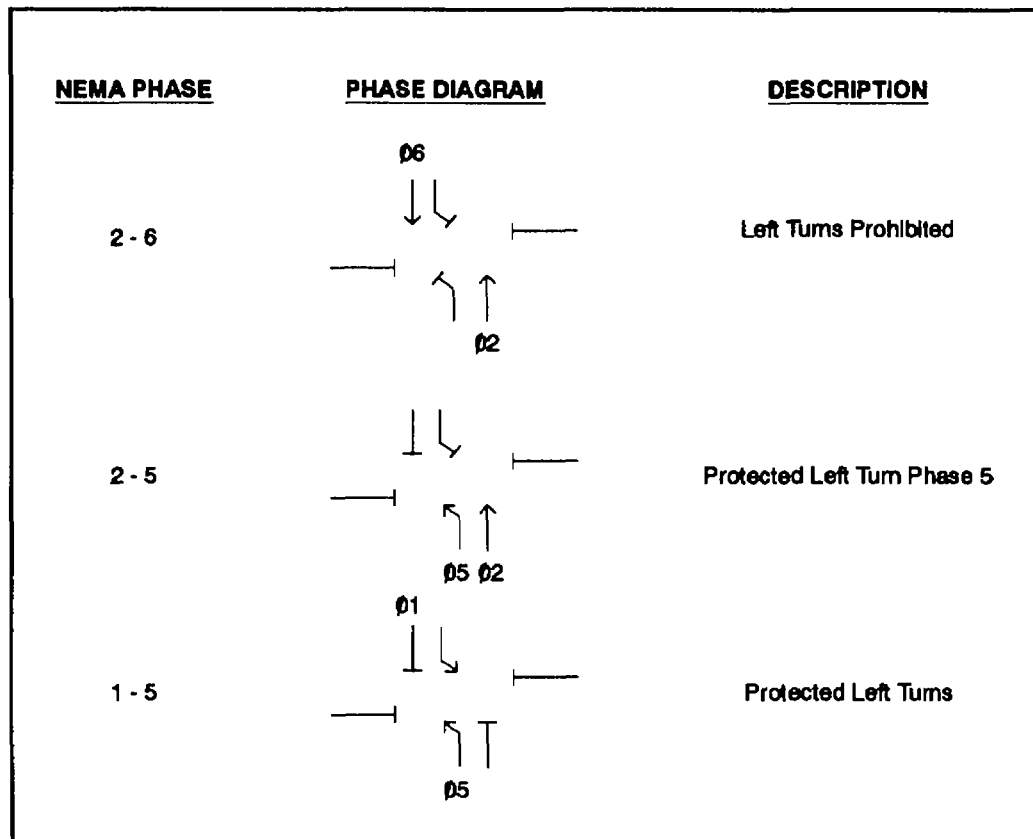


Figure 2-2. Phase Overlap with Protected Only Lagging Left

The data on delay, fuel consumption and auto emissions was based on a simulation model used by the Pima Association of Governments (3). Certainly these impressive figures merit further consideration of lagging left turn operation. The fact that this information is based on simulated data rather than field-measured data may reduce the impact of the findings, however. Additionally, there was a reported reduction in volume during the study which was apparently represented in the simulation model. This volume reduction could account for part of the delay reduction. The simulation run also considered a 10% lower cycle length with the lagging operation than the leading operation. This factor also would result in reduced delay being simulated. It should be noted that this study was based on limited data and only a six month after period.

A recent study prepared for the City of Scottsdale presented guidelines for the implementation of leading and lagging left turn phasing. It also considered the potential of third car actuated left turn phasing for protected/permissive operation. These guidelines are presented here (4, p.21):

Guidelines for Third Car Actuated - Leading Left Turn Phasing and Permitted/Protected -Lagging Left Turn Phasing:

When a traffic engineering study indicates that protected/permitted (leading) - permitted/protected (lagging) phasing is appropriate, a second decision is needed regarding lead versus lag. A basic conclusion of this study and premise for the following guidelines is that all leading-protected/

permitted operations should be third car actuated. This will reduce delay by enhancing intersection capacity and arterial travel speed. Recommended guidelines are:

1. Use Leading Protected/Permitted left turn phasing when:

- intersection is isolated and fully actuated
- intersection is in a coordinated system and leading left turns will enhance progressive movements, or leading left turns will provide for more efficient traffic flow than lagging.

2. Use Lagging-Permitted/Protected Left Turn Phasing when:

- intersection is in a coordinated system
- a capacity study and system operational analysis indicates that simultaneous lagging phasing offers operational benefits when compared to leading left turn phasing. (In some systems a combination of lead-lag phasing may be appropriate). There are several signal system simulation programs that can be used to generate key traffic operations "data" for use in the decision process. Specific data which should be considered are intersection capacity, level of service, delay, average speed, fuel consumption and emissions. Care should be taken to evaluate the left turn lane length requirements so as to avoid left turn traffic backing up into the through lanes. Such a backup can offset the other benefits of lagging left phasing.

It should be noted that at locations with protected left turns, lagging left phasing may offer operational benefits in comparison with leading left turn phasing. The guidelines discussed above should be followed in evaluating lead versus lag turns in a protected system.

Last, but not least, the City should develop a public information program including media notifications and temporary signing in conjunction with the implementation of lagging left turn-permitted/protected phasing.

The City of Scottsdale (5) reported a reduction in delay after going to lagging operation in 5 of 6 tests. This was based on AM peak, noon peak, and PM peak for both eastbound and westbound direction and is summarized in Table 2-1 (6, p.3). The city's study was based on five intersections along Thomas Road. Four of these five intersections were protected/permissive in the leading condition and were permissive/protected in the lagging condition. One intersection was protected only in the leading condition and permissive/protected in the lagging. All five intersections had phase overlap for eastbound and westbound approaches in the leading condition and simultaneous lagging arrows in the after condition. This study was based on travel time and delay data. The lagging operation

Table 2-1. City of Scottsdale Delay Study

Period and Direction	Delay Time, Seconds		Difference
	With Leading Arrows	With Lagging Arrows	
AM Peak - Eastbound	46	26	-20
AM Peak - Westbound	14	8	-6
Mid Peak - Eastbound	15	70	55
Mid Peak - Westbound	44	11	-33
PM Peak - Eastbound	88	59	-29
PM Peak - Westbound	53	30	-23

was a best fit offset selection into the previously developed signal plans. The change in delay could possibly be due to the random nature of the lagging left turn fitting into the time space diagram. The system progression was primarily determined by other streets with a higher priority (e.g. Scottsdale Road and Hayden Road). The research team on this current project performed the signal optimization study for the City of Scottsdale and assisted in the hand fitting of offsets on Thomas Road to optimize the operation of signals there within the previously determined signal timing patterns.

The number of intersection accidents in June and July of 1987 (with leading left turn operation) was compared with the same period in 1988 after lagging operation was implemented. The results are shown in Table 2-2 (6, p.2). Caution should be used in drawing conclusions from this data because of the short time period.

Table 2-2. City of Scottsdale Accident Data

Accident Type	With Leading Arrows	With Lagging Arrows
Left Turn	2	8
Rear End	7	6
Angle	2	2
Other	2	2
Total	13	18

The City of Mesa tested a leading/lagging operation on Alma School Road in 1988. The intersection of Grove and Holmes was converted from leading left both northbound and southbound to leading left in one direction and lagging in the other based on the time-space diagram.

Dramatic improvement was seen in the noon and evening periods after implementation of the new timing plan. During the noon period, northbound travel time decreased by 106 seconds (a 52% improvement), and southbound travel time decreased by 54 seconds (a 66% improvement). During the evening period, northbound travel time decreased by 61 seconds (a 65% improvement), and the southbound travel time decreased by 85 seconds (a 54% improvement). (7)

Research by Fambro and Woods (8) which was included in the Federal Highway Administration publication *Guidelines for Signalized Left Turn Treatments* indicates lagging left operation has an accident rate of twice that of leading. This information is presented in Table 2-3 (9, p.17).

Table 2-3. Relative Left-Turn Accident Rates for Various Left-Turn Signalization Schemes

Type of Left-Turn Phasing	Relative Accident Rate
Unprotected (Permissive)	1.00
Permissive/Protected - Lagging	0.73
Protected-Leading/Permissive	0.35
Protected	0.10

It is possible this is due to the previously discussed "trap" of lagging operation where the through movements do not terminate at the same time. This document states (9, p.13):

When selecting the type of left-turn signal phasing to install at an intersection, standardization often enters the picture. Some agencies recommend that only leading left-turn phasing be installed, while others recommend lagging left-turn phasing. In fact, there is one large city that uses two-phase (unprotected left-turn) signals exclusively. Uniformity and consistency in the type of signal phasing that is employed has inherent advantages in the area of driver expectancy. The motorists know the phasing arrangement to anticipate and can react accordingly; however, as demonstrated at actuated signals, this same group of drivers has proved adaptable to changes in signalization. Uniformity in left-turn phasing offers no proven safety benefit and in some situations does not result in the most efficient operation.

Of particular significance is the last sentence relating to the potential safety benefit of uniformity. This is particularly true when one considers the apparent perceived importance of uniformity demonstrated by the City of Tucson, Pima County, and the City of Scottsdale.

The FHWA publication also gives recommendations on phase selection. It states that there are system considerations of left turn phase selection (9, p.27):

Signals placed in a system configuration require consideration of the effects of the left-turn phasing on the system operation.

Dual Left-Turn Phasing. If the time space diagram indicates that traffic on each approach to the intersection arrives at the same time, dual left-turn phasing should be implemented.

Lead-Lag Left-Turn Phasing. If the time space diagram indicates that traffic on each approach to the intersection arrives at an appreciable difference in time (10 seconds or more) lead-lag phasing should be implemented.

A copy of Table 7 of the FHWA report is included in Appendix A which summarizes the phase selection guideline consideration for left turn phases. Because of the previously discussed potential safety problem of lagging permissive, it was determined that this research project consider these overlap phases and split phases in a protected only lagging operation.

A study by Machemehl which was based on a simulation model called TEXAS investigated various left turn sequence patterns at an isolated intersection. Machemehl reported (10, p.39):

In cases where split left-turn sequences are selected under actuated control, the question of which left-turn movement should lead a through movement green may arise. To determine whether the leading left-turn movement performs differently than the lagging movement in a split left-turn phase arrangement, 20 traffic approach demand combinations were compared for each of the two situations.

The results indicate that there is no significant difference in delay to left-turning or to through vehicles when a lagging phase is used instead of a leading phase, even though the required phase lengths are very different. This is because the left-turn queue discharges more efficiently with a leading phase minimizing delay to individual vehicles, but it requires a longer phase to do so, causing a longer cycle duration and more delay at the intersection. On the other hand, because the lagging phase is shorter, the main street green signal must be longer to process the through vehicles that would be processed with the left-turn vehicles with a leading phase. Thus, there is no significant difference between leading and lagging phases with split left turns and actuated control.

The literature search does not support the current phasing practices within the state, particularly the apparent need for standardization of either leading or lagging operation within the various governmental jurisdictions. Conversely, the literature generally recommends that the decision for leading versus lagging operation be based on conditions at the specific intersection and the opportunity to provide the best progression.

Even though the literature refers to the potential safety problem when terminating one through movement but not the other when going to a lag operation, it is not recognized to be as significant a problem as the local perception. The apparent source of the local importance is the Tucson experience of several lawsuits immediately after implementation of lagging left.

PART II

ACCIDENT STUDIES

PART II documents accident studies which were performed for three Arizona jurisdictions which have converted from leading to lagging operations.

CHAPTER 3 examines the accident experience in the City of Scottsdale. The Scottsdale accident analysis is based on a before and after comparison of the number of left turn accidents at nine intersections. The analysis compares three years of leading left arrow operation with one year of lagging operation. The Scottsdale accident analysis indicated no significant difference in the number of left turn accidents between a leading and a lagging operation.

CHAPTER 4 examines the accident experience in the Tucson area. The Pima County analysis is based on a before and after comparison of 21 intersections. The analysis, in most cases, compares two years of leading operation with two years of lagging operation. The City of Tucson analysis is based on a before and after comparison of 50 major arterial intersections and 12 intersections of major arterials with collector streets. The analysis compares three years of leading operation with two years of lagging operation. The analysis of left turn accidents in Pima County and the City of Tucson indicated that there were no significant differences resulting from the conversion from leading to lagging left turn operations.

CHAPTER 3

SCOTTSDALE ACCIDENT ANALYSIS

INTRODUCTION

The City of Scottsdale, in 1988, undertook a 10 week trial period of lagging left turn operation. Five intersections were converted from leading to lagging operations in June 1988. Based on the trial period experience, the City of Scottsdale converted an additional 45 signals to a lagging operation during the early part of 1989. Due to the brief history of lagging left turn operation in the City of Scottsdale, a one year lagging experience was compared with a three year leading experience. It is recognized that a multiple year after period would be more desirable due to the random nature of accidents and the multitude of factors which may influence roadway safety. For this reason, the statistical test which was selected for the analysis makes use of a control group which serves to discount the influence of extraneous factors and helps to identify general trends in accidents apart from the changes which may be attributed to the implementation of lagging left turn operation.

SELECTED INTERSECTIONS

The intersection selection process involved the development of an appropriate list for both the test and control intersections. The goal of the analysis is to assess the change in the number of accidents strictly as a function of the conversion from leading to lagging operation apart from any changes in protected or protected/permissive left turn phasing. Therefore, the test group was selected on the basis of similar operating conditions in the before and after period. If the intersection was operated in a permissive/protected phasing during the lagging operation then the intersection must have operated in the protected/permissive mode during the three year leading operation time period in order to be included in the test group. This constraint severely restricted the number of intersections which could be used in the analysis. Of the 50 intersections in the City of Scottsdale which were converted from a leading to a lagging operation only nine met this constraint. The test intersections used in the analysis are shown in Table 3-1. Also shown is the date of conversion from leading to lagging left turn phasing and the mode of operation before and after the conversion. One test intersection (Hayden Road/McDowell) was converted to dual left turn lanes in the last half of 1987. However, the intersection was retained in the analysis because it met the primary criteria of comparable signal operation in the before and after conditions.

Similar criteria were used to develop an appropriate set of control intersections. The primary reason for using a set of control intersections is to discount extraneous factors such as changes in traffic volumes, unusually inclement weather over some period of time, changes in accident reporting, etc. The secondary reason for using a set of control intersections is to identify unusual changes in the number of accidents as the result of purely random occurrences which may not be representative of long term trends. A set of 37 two phase intersections in the City of Scottsdale were used as the control group. Intersections which had undergone major reconstruction during the study period were not included in the set of control intersections. A list of the control intersections used in the analysis is presented in Table 3-2.

Table 3-1. Accident Analysis Test Intersections, City of Scottsdale

Intersection	Before Condition	Date of Conversion	After Condition
61st Pl./Thomas Rd.	Protected/Permissive	06/01/88	Permissive/Protected
Scottsdale Rd./Thomas Rd.	Protected/Permissive	06/01/88	Permissive/Protected
Hayden Rd./McDowell Rd.	Leading Protected	01/27/89	Lagging Protected
Miller Rd./Indian School Rd.	Protected/Permissive	02/02/89	Permissive/Protected
68th St./Indian School Rd.	Leading Protected	02/07/89	Lagging Protected
Hayden Rd./Chaparral	N/S Leading Protected	02/08/89	N/S Lagging Protected
Scottsdale Rd./Camelback Rd.	E/W Leading Protected	02/09/89	E/W Lagging Protected
Hayden Rd./McDonald Rd.	Leading Protected	02/14/89	Lagging Protected
Pima Rd./Shea Blvd.	Leading Protected	02/22/89	Lagging Protected

Table 3-2. Accident Analysis Control Intersections, City of Scottsdale

Intersection	Intersection
60th Street / Thomas	Scottsdale / Pinnacle Peak
64th Street / Camelback	Civic Center / Osborn
64th Street / Cactus	74th Street / McDowell
68th Street / Oak	75th Street / Indian School
68th Street / Osborn	Miller / McKellips
70th Street / McDowell	Miller / Chaparral
70th Street / Osborn	Miller / McDonald
70th Place / Camelback	Miller / Shea
71st Street / Camelback	77th Street / McDowell
71st Place / Shea	Hayden / Oak
Scottsdale / Roosevelt	Hayden / Jackrabbit
Scottsdale / Oak	Hayden / Indian Bend
Scottsdale / Earl	82nd Street / Indian School
Scottsdale / Fifth Avenue	Granite Reef / Thomas
Scottsdale / Fashion Square	Granite Reef / Camelback
Scottsdale / Jackrabbit	Granite Reef / Chaparral
Scottsdale / Mercer	Granite Reef / McDonald
Scottsdale / Cholla	Pima / Mountain View
Scottsdale / Sweetwater	

DATA COLLECTION

Accident data and information about each intersection was obtained from the Arizona Department of Transportation (ADOT) and the City of Scottsdale's Traffic Engineering Department. The primary source for accident data was the ADOT Accident Location Identification and Surveillance System (ALISS) data base. The summary reports generated by ALISS were manually reviewed to identify the accidents which were of interest to this study. Police accident reports were also used to supplement the data base.

The number of total intersection related accidents and the number of intersection related left turn accidents at each test intersection were recorded for each month from June 1985 to February 1990. For the purposes of this study, a left turn accident was defined as those accidents which were classified as "left turn" manner of collision or where either vehicle action was classified as "making left turn". Only those left turn accidents on the east and west approaches at the intersection of Scottsdale Road/Camelback Road and on the north and south approaches at the intersection of Hayden Road/Chaparral were recorded for the left turn accident analysis. The other approaches at these two intersections were not considered due to incomparable conditions in the before and after periods. The recorded accident data for the test intersections is shown in Table B-1 and Table B-2 in Appendix B.

The total number of intersection related accidents at each control intersection were also recorded for each month from June 1985 to February 1990. The recorded accident data for the control intersections is shown in Table B-3 in Appendix B.

ANALYSIS

The Scottsdale accident analysis is based on a before and after comparison of total intersection accidents and left turn accidents at nine test intersections. Due to the low number of accidents at most intersections it was necessary to develop a pool of intersections rather than testing each intersection individually. Two test intersections were converted to a lagging operation as part of the six month trial period starting in June 1988. The remaining seven test intersections were converted at various times in January and February 1989. Two sets of test intersections were developed to distinguish between protected/permissive operations and protected-only operations.

The first group of test intersections are those which have converted from a protected/permissive to a permissive/protected operation and includes the two intersections which were converted as part of the 10 week trial period. The before conversion time period for Group No. 1 extends from 1 June 1985 to 31 May 1988. The after conversion time period for Group No. 1 extends from 1 March 1989 to 28 February 1990.

The second group of test intersections are those which were converted in early 1989 from a leading protected-only to a lagging protected-only operation. The before conversion time period for Group No. 2 extends from 1 January 1986 to 31 December 1988. The after conversion time period for Group No. 2 extends from 1 March 1989 to 28 February 1990. Accident data was available only through the end of February 1990 at the time of the analysis.

The 37 control intersections were pooled for comparisons with the two test intersection groups. A

Table 3-3. Accident Analysis Summary Count, City of Scottsdale

Left Turn Accidents				
Group No. 1				
Test Intersections	Year			
	B3	B2	B1	A1
61st Place / Thomas	0	1	0	0
Scottsdale / Thomas	12	16	16	6
Miller / Indian School	7	6	5	6
Total	19	23	21	12
Control Intersections				
Total Accidents	230	286	269	219
Key:				
B3 = Jun 85 - May 86				
B2 = Jun 86 - May 87				
B1 = Jun 87 - May 88				
A1 = Mar 89 - Feb 90				
Group No. 2				
Test Intersections	Year			
	B3	B2	B1	A1
Hayden / McDowell	1	4	5	4
68th Street / Indian School Rd.	3	1	1	2
Scottsdale / Camelback	0	0	2	2
Hayden / Chaparral	1	1	1	1
Hayden / McDonald	2	0	2	2
Pima / Shea	0	0	1	0
Total	7	6	12	11
Total minus Hayden / McDowell	6	2	7	7
Control Intersections				
Total Accidents	260	284	237	219
Key:				
B3 = Jan 86 - Dec 86				
B2 = Jan 87 - Dec 87				
B1 = Jan 88 - Dec 88				
A1 = Mar 89 - Feb 90				
Total Intersection Accidents				
Group No. 1				
Test Intersections	Year			
	B3	B2	B1	A1
61st Place / Thomas	0	3	1	1
Scottsdale / Thomas	16	34	27	20
Miller / Indian School Rd	23	16	14	12
Total	39	53	42	33
Control Intersections				
Total Accidents	230	286	269	219
Key:				
B3 = Jun 85 - May 86				
B2 = Jun 86 - May 87				
B1 = Jun 87 - May 88				
A1 = Mar 89 - Feb 90				
Group No. 2				
Test Intersections	Year			
	B3	B2	B1	A1
Hayden / McDowell	17	22	21	26
68th Street / Indian School Rd	17	16	14	10
Hayden / Chaparral	9	10	10	7
Scottsdale / Camelback	14	10	16	16
Hayden / McDonald	9	16	20	13
Pima / Shea	5	5	13	8
Total	71	79	94	80
Total Minus Hayden / McDowell	54	57	73	54
Control Intersections				
Total Accidents	260	284	237	219
Key:				
B3 = Jan 86 - Dec 86				
B2 = Jan 87 - Jan 87				
B1 = Jan 88 - Dec 88				
A1 = Mar 89 - Feb 90				

summary of the number of accidents during the study period for both the test and the control intersections is shown in Table 3-3.

The statistical test used in the analysis is a chi-square goodness-of-fit test. The analysis involves two checks:

- (1) a test for comparability between the control intersections and the test intersections in the before period, and
- (2) a test of the effect of changing from leading to lagging left turns at the test intersections.

A cross product ratio was also calculated to measure the apparent effect of the conversion from leading to lagging left turn phasing relative to the control intersections. The chi-square test and cross product analyses are taken from a Texas Transportation Institute report: *Three Procedures for Evaluating Highway Safety Improvement Programs* by Lindsay I. Griffin, III. (11).

The test for comparability compares the test and control intersections using three years of before data. A test for comparability in the after period could not be performed due to the fact only one year of after data was available. The results of these tests are presented in Table 3-4. The calculated chi-square for Group 1 left turn accidents was 0.03 ($p=0.98$) which indicates a strong comparability with the control intersections. The calculated chi-square for Group 2 left turn accidents was 3.48 ($p=0.18$) which indicates Group 2 is not very comparable to the control group. Therefore, the use of the control group to measure the effect of the lead to lag conversion should be viewed with caution. The comparability of Group 2 minus the Hayden/McDowell intersection (Group 2A) was also evaluated. The results indicate an even weaker level of comparability ($G^2=4.15$, $df=2$, $p=0.13$). The calculated chi-square for Group 1 total intersection accidents was 0.59 ($p=0.75$) which again indicates good comparability between Group 1 and the control intersections. The calculated chi-square for Group 2 ($G^2=5.59$, $p=0.064$) and Group 2A ($G^2=5.81$, $p=0.056$) indicates that Group 2 total intersection accident results are not very comparable to the control intersections. Therefore, the estimate of the effect of the Group 2 lead to lag conversion relative to the control intersections should be viewed with extreme caution.

The test of treatment compares the before and after changes at the test intersections relative to the changes at the control intersections. The results of the test are presented in Table 3-5. Group 1 left turn accidents decreased 32% relative to the control intersections ($G^2=1.49$, $df=1$, $p=0.23$) with the conversion from leading (protected/permmissive) to lagging (permmissive/protected) phasing. Group 2 left turn accidents showed an increase of 57% ($G^2=1.40$, $p=0.24$) relative to the control

Table 3-4. Accident Analysis Test for Comparability, City of Scottsdale

Group	Left Turn Accidents		Total Accidents	
	Comparability	Level of Significance	Comparability	Level of Significance
	Test Statistic	(p)	Test Statistic	(p)
1	0.03	0.98	0.59	0.75
2	3.48	0.18	5.59	0.064
2A	4.15	0.13	5.81	0.056

Table 3-5. Accident Analysis Test of Treatment, City of Scottsdale

Group	Left Turn Accidents			Total Accidents		
	Treatment Test Statistic	Level of Significance (p)	Change (%)	Treatment Test Statistic	Level of Significance (p)	Change (%)
1	1.49	0.23	-32%	0.36	0.56	-12%
2	1.40	0.24	57%	1.08	0.30	17%
2A	1.13	0.29	66%	0.07	0.79	5%

intersections. With the conversion from leading to lagging phasing the results were similar for Group 2 minus Hayden/McDowell (Group 2A) with an apparent increase of 66% ($G^2=1.13$, $p=0.29$). Group 1 total intersection accidents decreased 12% relative to the control intersections ($G^2=0.36$, $p=0.56$) with the conversion. Group 2 total intersection accidents showed an increase of 17% ($G^2=1.08$, $p=0.30$) relative to the control intersections and Group 2A a slight increase of 5% ($G^2=0.07$, $p=0.79$) with the change for leading protected to lagging protected phasing.

The significance of these Group 2 changes is questionable due to the lack of comparability between the Group 2 intersections and the control intersections. Therefore, a simple before/after test was also performed to evaluate the absolute change in the number of accidents independent of the control intersections. The results are presented in Table 3-6. The reduction in the number of accidents at the Group 1 intersections become more pronounced when evaluated independent of the control intersections. Group 1 left accidents declined 43% ($p=0.12$) and total intersection accidents declined 26% ($p=0.18$). The increase in the number of accidents at the Group 2 intersections becomes less pronounced when evaluated independent of the control intersections. Group 2 left turn accidents increased 32% ($p=0.54$) and total accidents show a slight increase of 7% to ($p=0.66$). Group 2A provided similar results except the total intersection accidents show a slight decrease of 12% ($p=0.49$) when the Hayden/McDowell intersection is removed from the group. The high p-values indicate a low probability of any statistically significant difference in the number of accidents at the Group 2 intersections in the before and after periods.

DISCUSSION OF RESULTS

The Scottsdale accident analysis indicates no statistically significant change at the 90% confidence level in the number of left turn accidents or in the number of total intersection related accidents, with the conversion from leading to lagging left turns. The analysis which was applied utilized a comparison group and a test for comparability to evaluate the change in number of accidents. Also, extreme care was exercised in the selection of both the test and control intersections to ensure the analysis isolated strictly on the effects of the conversion from leading to lagging without allowing any extraneous factors to either into the evaluation. The test is admittedly rigorous and the number of intersections which could be analyzed was limited. The small sample size contributed to the finding of no statistically significant change.

However, the apparent decrease for Group 1 coupled with the apparent increase in Group 2 seems to indicate that the impact of lagging operation on left turn accidents may be different for protected/permitted and protected only intersections. The apparent decrease in accidents with the conversion from protected/permitted leading operation to a permitted/protected lagging operation indicates people may be less likely to turn across a gap in the permissive phase given the knowledge that a

Table 3-6. Accident Analysis Results, City of Scottsdale**Left Turn Accidents**

Group	Leading (acc/yr)	Lagging (acc/yr)	Absolute Change (%)	Test Statistic (Z)	Level of Significance (p)	Relative Change*
1	21	12	-42.9%	-1.57	0.12	-31.7%
2	8.3	11	32.0%	0.61	0.54	56.9%
2A	5	7	40.0%	0.58	0.56	66.4%

Total Intersection Accidents

Group	Leading (acc/yr)	Lagging (acc/yr)	Absolute Change (%)	Test Statistic (Z)	Level of Significance (p)	Relative Change*
1	44.7	33	-26.1%	-1.32	0.18	-11.7%
2	74.7	80	7.1%	0.43	0.66	16.9%
2A	61.3	54	-12.0%	0.68	0.49	4.7%

* Change relative to the control intersections.

Group 2A is Group 2 minus the Hayden / McDowell Intersection.

protected left turn can be executed at the end of the permitted phase. This same safety advantage would not be realized with the conversion from a protected-only leading to protected-only lagging operation.

The availability of accident data did not allow for a three month driver adjustment period at all intersections. However, the lagging left turn was not completely new to City of Scottsdale drivers at the time these intersections were converted. They had just participated in a 10 week trial period of lagging operation at five locations in the City of Scottsdale. Nevertheless, further analysis should be performed as this data becomes available.

Finally, it should be noted that the number of reported accidents in the City of Scottsdale has generally declined over the past few years. This is evidenced by the general decline in the number of accidents recorded at the control intersections for the last year before conversion and the first year after conversion. The City of Scottsdale's Traffic Engineering Department is not aware of any particular changes which may have brought about this welcomed event. However, in terms of the analysis performed, this put added pressure on the limited number of test intersections analyzed to show commensurate declines.

CHAPTER 4

PIMA COUNTY/TUCSON ACCIDENT STUDIES

As part of this research project, an analysis of the accident experience in the Tucson area was undertaken. This analysis involved an examination of accidents at signalized intersections before and after the conversion from leading to lagging turns. Accident data from the City of Tucson as well as Pima County were utilized in the study; however the experience of each jurisdiction was analyzed separately. The purpose of this chapter is to document the data collection, analysis, and results of the study.

PIMA COUNTY ANALYSIS

Introduction

The conversion from leading to lagging left turn operation at signalized intersections under the control of Pima County occurred in 1987. At that time, Pima County had a total of 37 intersections which were converted. This constituted virtually all of signalized intersections under the control of Pima County. In addition to the conversion from leading to lagging left turn operation, other operational changes were made at a number of intersections. These operational changes, lack of data, or annexation by the City of Tucson necessitated the elimination of some of the intersections from the accident study. As a result, the analysis included a total of 21 intersections which are listed in Table 4-1. The type of left turn operation by approach is also shown in the table. As may be noted from the information in Table 4-1, most of the study approaches utilized protected/permitted left turn operations. A limited number of the approaches had protected only left turn movements. Two of the approaches included in the study had protected/permitted left turn operations in the before period. Changes in intersection signal operations at these two intersections resulted in protected only movements in the after period.

Data Collection

For the analysis of the Pima County signalized intersections, data and information about each of the intersections were obtained from the records of the Pima County Department of Transportation. For each of the intersections, the following data and information were obtained:

- date of conversion from leading to lagging left turn operation
- accident data for the before and after periods
- signal timing plans
- estimated traffic volumes
- Other relevant information relative to changes in design operation of the intersection.

The records maintained by the Pima County Department of Transportation yielded detailed information about the intersections. For example, it was possible to obtain collision diagrams for each intersection as well as accident summaries. In addition, the accidents could be analyzed by type and intersection approach.

Table 4-1. Number of Left-Turn Accidents, Pima County

Intersection	Direction	Number of Accidents Before	Number of Accidents After
Ajo Way / Palo Verde Rd.	Northbound	0	1
	Southbound	2	0
Alvernon Way / Irvington Rd.	Southbound	0	0
	Eastbound	0	7
Alvernon Way / Valencia Rd.	Eastbound	1	7
	Westbound	4	0
Campbell Ave. / River Rd.	Northbound (P)	1	8
	Westbound	5	6
Craycroft Ave. / River Rd.	Southbound	3	4
	Westbound	0	0
Craycroft Ave. / Sunrise Dr.	Northbound	0	0
Dodge Blvd. / River Rd.	Westbound	1	1
Dos Hombres / Tanque Verde Rd.	Eastbound	2	1
	Westbound	2	1
First Ave. / Ina Rd.	Northbound (*)	1	0
First Ave. / Orange Grove Rd.	Northbound	3	1
	Southbound	1	0
First Ave. / River Rd.	Northbound	1	3
	Southbound	3	5
Ina Rd. / La Canada Dr.	Eastbound	3	10
	Westbound	1	2
Ina Rd. / La Cholla Blvd.	Eastbound	2	2
	Westbound	4	5
Ina Rd. / Oldfather Rd.	Eastbound	0	3
Ina Rd. / Thornydale Rd.	Northbound	2	9
	Southbound	1	5
	Eastbound	2	1
	Westbound	4	0
Kolb Rd. / Valencia Rd.	Northbound (P)	0	0
	Southbound (P)	0	0
	Eastbound (P)	2	0
	Westbound (P)	0	0
La Cholla Blvd. / Orange Grove Rd.	Northbound (P)	0	0
	Southbound (P)	0	1
	Eastbound (P)	0	1
	Westbound (P)	1	0
Mission Rd. / Valencia Rd.	Eastbound	0	2
	Westbound	3	3
Orange Grove Rd. / Skyline Dr.	Northbound (P)	8	13
River Rd. / Swan Rd.	Northbound	3	6
	Westbound	0	0
Sunrise Dr. / Swan Rd.	Southbound (*)	2	0

(P) - Protected only left turns.

(*) - Protected / permitted left turns in the before period and protected left turns in the after period.

Because the actual dates of conversion from leading to lagging left turn operation were known, the before period was defined as two years preceding the conversion in 1987. In some cases, it was not possible to obtain a full two years of accident data at an intersection due to other factors such as the date of signal installation. The actual number of days in the analysis periods for each of the intersections are indicated in a later section of this report.

For the analysis, a three month driver adjustment was used; thus the after period commenced three months following the conversion at an intersection. The after period then included all accidents from three months after the conversion of the signal operation until November 30, 1989. This cut-off date was necessitated by the data collection process; however it resulted in an after period of over two years at each of the intersections.

Analysis

During the process of converting from leading to lagging left turn operation, Pima County re-evaluated the need for protected turn movements at the intersections. This resulted in left turn phases being added or deleted at many of the intersections listed in Table 4-1. In order to maintain a reasonable data base, the intersections were analyzed on the basis of the individual approaches. For example, the evaluation focused on left turn accidents on the intersection approaches where the conversion from leading to lagging operation had occurred. Intersection approaches where other changes had been made (such as the addition or deletion of a left turn phase) were not included in the final analysis. In this way, accidents that were directly associated with the leading and lagging left turn operations were isolated for comparison.

Table 4-1 indicates the number of left turn accidents that were reported during the before and after periods at each intersection. The accidents are shown by approach for each of the intersections. For this study, an accident was considered to be a left turn accident if a left turning vehicle on a given approach was involved.

As indicated previously, the initial intent was to obtain the accident records for a two year period prior to the signal operation conversion. In some cases, this was not possible. The after period for all of the intersections was greater than two years with the exception of one which had an after period of a few days less than two years. The number of days in the before and after periods of each intersection is shown in Table C-1 in Appendix C.

Using the number of reported accidents and the durations of the before and after periods, the equivalent number of accidents per year was calculated for each study approach. This information is presented in Table 4-2.

It should be noted that accidents involving bicycles were not included in the analysis. At all of the intersections, there were only two bicycle related accidents in the before period and one in the after period.

The average daily volumes for each of the intersection approaches were obtained from the Pima County Department of Transportation. The estimated average daily approach volumes for the before and after periods are given in Table 4-3. These values reflect the total volume for an intersection

Table 4-2. Equivalent Number of Accidents per Year, Pima County

Intersection	Direction	Number of Accidents Per Year		
		Before	After	Difference
Ajo Way / Palo Verde Rd.	Northbound	0.00	0.41	0.41
	Southbound	1.00	0.00	-1.00
Alvernon Way / Irvington Rd.	Southbound	0.00	0.00	0.00
	Eastbound	0.00	2.90	2.90
Alvernon Way / Valencia Rd.	Eastbound	0.50	2.89	2.39
	Westbound	2.00	0.00	-2.00
Campbell Ave. / River Rd.	Northbound (P)	0.50	3.39	2.89
	Westbound	2.50	2.54	0.04
Craycroft Ave. / River Rd.	Southbound	1.50	1.69	0.19
	Westbound	0.00	0.00	0.00
Craycroft Ave. / Sunrise Dr.	Northbound	0.00	0.00	0.00
Dodge Blvd. / River Rd.	Westbound	0.88	0.42	-0.46
Dos Hombres / Tanque Verde Rd.	Eastbound	1.00	0.43	-0.57
	Westbound	1.00	0.43	-0.57
First Ave. / Ina Rd.	Northbound (*)	0.50	0.00	-0.50
First Ave. / Orange Grove Rd.	Northbound	1.50	0.42	-1.08
	Southbound	0.50	0.00	-0.50
First Ave. / River Rd.	Northbound	1.59	1.25	-0.34
	Southbound	4.76	2.08	-2.68
Ina Rd. / La Canada Dr.	Eastbound	1.50	4.31	2.81
	Westbound	0.50	0.86	0.36
Ina Rd. / La Cholla Blvd.	Eastbound	1.00	0.86	-0.14
	Westbound	2.00	2.16	0.16
Ina Rd. / Oldfather Rd.	Eastbound	0.00	1.33	1.33
Ina Rd. / Thornydale Rd.	Northbound	1.00	3.96	2.96
	Southbound	0.50	2.20	1.70
	Eastbound	1.00	0.44	-0.56
	Westbound	2.00	0.00	-2.00
Kolb Rd. / Valencia Rd.	Northbound (P)	0.00	0.00	0.00
	Southbound (P)	0.00	0.00	0.00
	Eastbound (P)	2.25	0.00	-2.25
	Westbound (P)	0.00	0.00	0.00
La Cholla Blvd. / Orange Grove Rd.	Northbound (P)	0.00	0.00	0.00
	Southbound (P)	0.00	0.42	0.42
	Eastbound (P)	0.00	0.42	0.42
	Westbound (P)	1.10	0.00	-1.10
Mission Rd. / Valencia Rd.	Eastbound	0.00	0.83	0.83
	Westbound	1.50	1.24	-0.26
Orange Grove Rd. / Skyline Dr.	Northbound (P)	4.00	5.51	1.51
River Rd. / Swan Rd.	Northbound	1.95	3.08	1.13
	Westbound	0.00	0.00	0.00
Sunrise Dr. / Swan Rd.	Southbound (*)	0.80	0.00	0.80

(P) - Protected only left turns

(*) - Protected / permitted left turns in the before period and protected left turns in the after period

Table 4-3. Estimated Approach Volumes, Pima County

Intersection	Direction	Approach Volumes	
		Before (vpd)	After (vpd)
Ajo Way / Palo Verde Rd.	Northbound	14,709	12,127
	Southbound	15,210	11,376
Alvernon Way / Irvington Rd.	Southbound	7,490	13,788
	Eastbound	6,104	6,256
Alvernon Way / Valencia Rd.	Eastbound	9,624	10,703
	Westbound	10,203	7,854
Campbell Ave. / River Rd.	Northbound	12,062	13,568
	Westbound	8,078	10,040
Craycroft Ave. / River Rd.	Southbound	7,456	7,607
	Westbound	4,231	6,415
Craycroft Ave. / Sunrise Dr.	Northbound	6,450	7,856
Dodge Blvd. / River Rd.	Westbound	5,169	8,004
Dos Hombres / Tanque Verde Rd.	Eastbound	16,010	18,959
	Westbound	16,610	17,384
First Ave. / Ina Rd.	Northbound	4,763	5,547
First Ave. / Orange Grove Rd.	Northbound	8,683	9,059
	Southbound	5,231	5,268
First Ave. / River Rd.	Northbound	11,428	11,914
	Southbound	11,002	11,710
Ina Rd. / La Canada Dr.	Eastbound	12,664	15,054
	Westbound	12,460	14,488
Ina Rd. / La Cholla Blvd.	Eastbound	11,612	15,202
	Westbound	13,527	15,860
Ina Rd. / Oldfather Rd.	Eastbound	12,942	14,808
Ina Rd. / Thornydale Rd.	Northbound	6,740	8,383
	Southbound	5,804	8,414
	Eastbound	11,782	14,242
	Westbound	10,525	19,253
Kolb Rd. / Valencia Rd.	Northbound	3,972	3,970
	Southbound	9,863	12,418
	Eastbound	8,429	8,098
	Westbound	1,105	1,205
La Cholla Blvd. / Orange Grove Rd.	Northbound	8,058	7,610
	Southbound	4,219	5,815
	Eastbound	6,113	6,244
	Westbound	7,871	8,119
Mission Rd. / Valencia Rd.	Eastbound	8,695	10,475
	Westbound	11,625	12,878
Orange Grove Rd. / Skyline Dr.	Northbound	10,571	12,417
River Rd. / Swan Rd.	Northbound	9,644	11,655
	Westbound	2,372	3,548
Sunrise Dr. / Swan Rd.	Southbound	4,704	4,231

approach. While it would have been desirable to have only the left turn approach volume, this level of detail was not available.

It is recognized that the true left turn accident rate should be based on the volume of left turn vehicles entering the intersection. Because this information was not available, the accident rate was based on the total approach volume. In this way, the influence of exposure and the durations of the study periods were considered. In view of the fact that the before and after periods were separated only by a three month driver adjustment period, it would be expected that the proportion of left turning vehicles in the approach volumes would remain about the same. The accident rate (based on the total approach volume) for each of the intersection approaches is shown in Table 4-4.

A number of different statistical tests have historically been applied to accident analyses. Typically, these analyses evaluate differences in accidents or the average accident rate. In some cases, differences in accident rates for the before and after periods are compared with the experience at other intersections which were not subjected to a given treatment.

After considering the nature of the data set, it was decided to apply the Wilcoxon Signed-Ranks Test. Basically, the test examines the direction of the difference within a sample pair as well as the relative magnitude of the difference. It provides a means of analyzing the experience for each of the intersection approaches in addition to examining the collective results of the total sample.

An analysis of the total intersection accidents was also undertaken for the purpose of examining any possible effect of the change in left turn operation on the total intersection safety. In order to eliminate possible impacts of other changes at the intersections, only the accidents associated with the approaches included in the left turn study were evaluated. Appendix C contains tables which summarize the data for all accidents on the approaches considered.

Discussion of Results

The summary results of the Wilcoxon test based on accident rates are presented in Table C-2 in Appendix C. In reviewing Table C-2, it may be noted that some of the intersection approaches are not listed in the table. This is due to the fact that samples with no difference in the before and after periods are dropped from the statistical test. Only the intersection approaches for which there was a difference in the accident rate are shown in Table C-2. Similar information for the analysis of the equivalent number of accidents is given in Table C-3 in Appendix C. Also, information related to the analysis of total intersection accidents is in Appendix C.

For the analyses, the null hypothesis was that there is no difference in the accident experience for the before and after periods. At the 95 percent confidence level, the analyses indicate that the hypothesis should be accepted in both cases. In essence, the use of accident rates, the use of the equivalent number of left turn accidents, or the use of total accident data yielded the same results. The conclusion, therefore, is that there was no difference in the accident experience.

While the Wilcoxon test did not indicate statistical significance, the actual change in number of accidents was calculated for the left turn accidents and the total accidents. Based on the number of accidents per year, there was a 13.8 percent increase in left turn accidents while the total accidents decreased by 1.5 percent.

Table 4-4. Left-Turn Accident Rate, Pima County

Intersection	Direction	Accident Rate (Accidents / Million Entering Vehicles)		
		Before	After	Difference
Ajo Way / Palo Verde Rd.	Northbound	0.000	0.094	- 0.094
	Southbound	0.180	0.000	+ 0.180
Alvermon Way / Irvington Rd.	Southbound	0.000	0.000	
	Eastbound	0.000	1.274	- 1.274
Alvermon Way / Valencia Rd.	Eastbound	0.142	0.740	- 0.598
	Westbound	0.537	0.000	+ 0.537
Campbell Ave. / River Rd.	Northbound (P)	0.114	0.683	- 0.569
	Westbound	0.848	0.693	+ 0.155
Craycroft Ave. / River Rd.	Southbound	0.551	0.611	- 0.060
	Westbound	0.000	0.000	
Craycroft Ave. / Sunrise Dr.	Northbound	0.000	0.000	
Dodge Blvd. / River Rd.	Westbound	0.464	0.145	+ 0.319
Dos Hombres / Tanque Verde Rd.	Eastbound	0.171	0.062	+ 0.109
	Westbound	0.165	0.067	+ 0.098
First Ave. / Ina Rd.	Northbound (*)	0.288	0.000	+ 0.288
First Ave. / Orange Grove Rd.	Northbound	0.473	0.629	- 0.156
	Southbound	0.262	0.000	+ 0.262
First Ave. / River Rd.	Northbound	0.379	0.287	+ 0.092
	Southbound	1.180	0.487	+ 0.693
Ina Rd. / La Canada Dr.	Eastbound	0.325	0.783	- 0.458
	Westbound	0.110	0.163	- 0.053
Ina Rd. / La Cholla Blvd.	Eastbound	0.236	0.155	+ 0.081
	Westbound	0.405	0.372	+ 0.033
Ina Rd. / Oldfather Rd.	Eastbound	0.000	0.245	- 0.245
Ina Rd. / Thornydale Rd.	Northbound	0.407	1.298	- 0.891
	Southbound	0.236	0.719	- 0.483
	Eastbound	0.233	0.085	+ 0.148
	Westbound	0.521	0.000	+ 0.521
Kolb Rd. / Valencia Rd.	Northbound (P)	0.000	0.000	
	Southbound (P)	0.000	0.000	
	Eastbound (P)	0.730	0.000	+ 0.730
	Westbound (P)	0.000	0.000	
La Cholla Blvd. / Orange Grove Rd.	Northbound (P)	0.000	0.000	
	Southbound (P)	0.000	0.197	- 0.197
	Eastbound (P)	0.000	0.184	- 0.184
	Westbound (P)	0.384	0.000	+ 0.384
Mission Rd. / Valencia Rd.	Eastbound	0.000	0.216	- 0.216
	Westbound	0.354	0.264	+ 0.090
Orange Grove Rd. / Skyline Dr.	Northbound (P)	1.037	1.213	- 0.176
River Rd. / Swan Rd.	Northbound	0.554	0.724	- 0.170
	Westbound	0.000	0.000	
Sunrise Dr. / Swan Rd.	Southbound (*)	0.466	0.000	+ 0.466

(P) - Protected only left turns

(*) - Protected / permitted left turns in the before period and protected left turns in the after period

Because the Wilcoxon test examines the experience at each intersection, the analysis was undertaken by including all of the approaches into a single group. In this way, the collective result of the conversion to lagging left turns was analyzed. It can be argued that the analysis should be accomplished by considering the approaches with protected/permitted operations separate from the approaches with protected only operations. Subsequent evaluation of the approaches separated by type of operation also indicated variation in the accident experience in both group with no statistical difference at the 95 percent confidence level.

CITY OF TUCSON ANALYSIS

Introduction

The conversion from leading to lagging left turn operation in the City of Tucson was accomplished in 1985. At that time, virtually all traffic signals in the City with protected left turn phases were converted to the lagging left turn operation. In the City of Tucson, the practice is to use permitted left turns with the protected movement.

For the evaluation of the accident experience in the City of Tucson, a "before and after" type of analysis was again used. Some of the detailed information about accidents as well as the intersections was not readily available; thus a slightly different approach was taken for the analysis.

Data Collection

The City of Tucson furnished computer summaries of intersection accident data. Because the conversion in signal operation occurred in 1985, that year was eliminated from the analysis. Data for a before period from 1982 to 1984 and an after period of 1986 to 1987 were compiled by the City from the computerized accident records. The information indicated the total accident rate for an intersection as well as the number of accidents by general types. Again, an accident was considered to be a left turn accident if a left turner was involved.

The City also sorts the intersections by type. For example, the data was compiled for the intersection of major arterial streets and for the intersection of major arterials with collector streets. Generally, signals at the intersection of major arterials will have protected left turn phases on all approaches; and signals at intersections with collector streets will have left turn phases on the major arterial approaches.

As was the case with the Pima County situation, it was necessary to screen the list of intersections for the purpose of eliminating those where other obvious changes had been made. This resulted in 50 intersections involving major arterials and 12 intersections of major arterials with collector streets being included in the study.

Analysis

For the analysis, the initial problem was to find a method for determining the left turn accident rates. The total approach volumes were available for each intersection; however the left turn volumes were unknown. Thus, it was not possible to directly determine the left turn accident rate at each of the intersections. As a surrogate measure, the left turn accident rate was calculated by multiplying the

total intersection accident rate by the ratio of left turn accidents to all accidents. In essence, this resulted in a value that is based on the total left turn accidents within the intersection, the average total entering intersection volumes, and the time period over which the data were gathered. The summaries of information used for both intersection groups are shown in Tables 4-5 through 4-10.

The Wilcoxon test was also utilized to statistically evaluate the experience in the before and after periods. This analysis was accomplished for each of the two groups of intersections using accident rates as well as the number of accidents per year. The results of the statistical tests are in Tables C-4 through C-7. As was the case with the Pima County intersections, it was concluded that there was no significant difference in the before and after accident experience.

For the two categories of City of Tucson intersections, the total intersection accidents were also compiled. This compilation included an examination of all reported accidents at each of the intersections. The summary tables indicating the total intersection accident experience are included in Appendix C. Again, the analysis of all accidents did not indicate any statistical difference in total accident experience.

Discussion of Results

The analysis of left turn accidents in Pima County and the City of Tucson indicated that there were no significant differences resulting from the conversion from leading to lagging left turn operations. This finding is somewhat contrary to the comments in the literature that indicate that the lagging left turn operation results in a more hazardous condition.

The examination of the change in the number of accidents per year yielded the following results for the before and after periods:

- At the intersection of major arterial streets, the number of left turn accidents decreased by 2.8 percent while all accidents decreased by 6.1 percent.
- For the group of intersections involving major arterials and collector streets, the left turn accidents decrease by 11.3 percent and all accidents decreased by 17.8 percent.

Certainly, a review of the accident experience at the individual intersections reveals considerable variation in the results. At some intersections, there were large increases or decreases in accidents. There was nothing in the available information about the intersections that would explain these variations other than the random nature of accidents.

It should be noted that in Pima County as well as the City of Tucson lagging protected left turn phase overlaps are not used in conjunction with permitted left turn operations. This means that the relatively hazardous "left turn trap" condition does not occur. For this reason, it is not surprising that a difference was not found between the leading and lagging conditions.

Some traffic engineers will suggest that the lagging left turn operation is safer because the motorist knows that the left turn can be made at the end of the permitted phase. In this case, the driver is not as pressured to make the permitted left turn. Generally, the City of Tucson uses permitted/protected left turn operations at intersections with protected left turn phases. Again, the data did not reveal any significant differences.

Table 4-5. Left-Turn Accidents, City of Tucson Arterial / Arterial Intersections

Intersection	Number of Left Turn Accidents	
	1982 - 1984	1986 - 1987
Ajo Way / Mission Rd.	18	13
Ajo Way / Interstate 19	0	0
Ajo Way / 12th Ave.	24	10
Alvernon Way / Broadway Blvd.	23	9
Alvernon Way / 22nd St.	111	41
Broadway Blvd. / Campbell Ave.	14	26
Broadway Blvd. / Country Club Rd.	17	14
Broadway Blvd. / Craycroft Rd.	16	8
Broadway Blvd. / Kolb Rd.	16	11
Broadway Blvd. / Swan Rd.	16	9
Broadway Blvd. / Wilmot Rd.	24	7
Campbell Ave. / Fort Lowell Rd.	35	16
Campbell Ave. / Grant Rd.	28	26
Campbell Ave. / Speedway Blvd.	31	21
Congress St. / Granada Ave.	3	3
Congress St. / Interstate 10	20	9
Country Club Rd. / Grant Rd.	11	13
Country Club Rd. / Speedway Blvd.	10	6
Country Club Rd. / Valencia Rd.	4	6
Craycroft Rd. / Golf Links Rd.	9	21
Craycroft Rd. / 22nd St.	46	32
Fort Lowell Rd. / Oracle Rd.	3	16
Golf Links Rd. / Kolb Rd.	16	16
Golf Links Rd. / Wilmot Rd.	24	18
Grant Rd. / Oracle Rd.	24	18
Grant Rd. / Stone Ave.	21	13
Grant Rd. / Swan Rd.	30	15
Grant (Kolb) Rd. / Tanque Verde Rd.	36	27
Grant Rd. / First Ave.	21	7
Grant Rd. / Interstate 10	2	13
Kolb Rd. / Speedway Blvd.	28	14
Kolb Rd. / 22nd St.	55	27
Main Ave. / Speedway Blvd.	13	5
Miracle Mile / Oracle Rd.	2	14
Nogales Highway / Valencia Rd.	28	13
Oracle Rd. / Prince Rd.	34	26
Oracle Rd. / River Rd.	5	8
Oracle Rd. / Wetmore Rd.	3	11
Speedway Blvd. / Stone Ave.	20	10
Speedway Blvd. / Swan Rd.	5	3
Speedway Blvd. / Wilmot Rd.	12	12
Speedway Blvd. / Interstate 10	9	3
St. Mary's Rd. / Interstate 10	14	3
Swan Rd. / 22nd St.	43	5
Valencia Rd. / 12th Ave.	20	12
Wetmore Rd. / First Ave.	7	5
Wilmot Rd. / 5th St.	12	9
Wilmot Rd. / 22nd St.	39	29
Interstate 10 / 22nd St.	12	5
5th Ave. / Interstate 10	5	2

Table 4-6. Average Left-Turn Accidents per Year, City of Tucson Arterial / Arterial Intersections

Intersection	Left Turn Accidents Per Year		
	Before	After	Difference
Ajo Way / Mission Rd.	6.00	6.50	0.50
Ajo Way / Interstate 19	0.00	0.00	0.00
Ajo Way / 12th Ave.	8.00	5.00	-3.00
Alvernon Way / Broadway Blvd.	7.67	4.50	-3.17
Alvernon Way / 22nd St.	37.00	20.50	-16.50
Broadway Blvd. / Campbell Ave.	4.67	13.00	8.33
Broadway Blvd. / Country Club Rd.	5.67	7.00	1.33
Broadway Blvd. / Craycroft Rd.	5.33	4.00	-1.33
Broadway Blvd. / Kolb Rd.	5.33	5.50	0.17
Broadway Blvd. / Swan Rd.	5.33	4.50	-0.83
Broadway Blvd. / Wilmot Rd.	8.00	3.50	-4.50
Campbell Ave. / Fort Lowell Rd.	11.67	8.00	-3.67
Campbell Ave. / Grant Rd.	9.33	13.00	3.67
Campbell Ave. / Speedway Blvd.	10.33	10.50	0.17
Congress St. / Granada Ave.	1.00	1.50	0.50
Congress St. / Interstate 10	6.67	4.50	-2.17
Country Club Rd. / Grant Rd.	3.67	6.50	2.83
Country Club Rd. / Speedway Blvd.	3.33	3.00	-0.33
Country Club Rd. / Valencia Rd.	1.33	3.00	1.67
Craycroft Rd. / Golf Links Rd.	3.00	10.50	7.50
Craycroft Rd. / 22nd St.	15.33	16.00	0.67
Fort Lowell Rd. / Oracle Rd.	1.00	8.00	7.00
Golf Links Rd. / Kolb Rd.	5.33	8.00	2.67
Golf Links Rd. / Wilmot Rd.	8.00	9.00	1.00
Grant Rd. / Oracle Rd.	8.00	9.00	1.00
Grant Rd. / Stone Ave.	7.00	6.50	-0.50
Grant Rd. / Swan Rd.	10.00	7.50	-2.50
Grant (Kolb) Rd. / Tanque Verde Rd.	12.00	13.50	1.50
Grant Rd. / First Ave.	7.00	3.50	-3.50
Grant Rd. / Interstate 10	0.67	6.50	5.83
Kolb Rd. / Speedway Blvd.	9.33	7.00	-2.33
Kolb Rd. / 22nd St.	18.33	13.50	-4.83
Main Ave. / Speedway Blvd.	4.33	2.50	-1.83
Miracle Mile / Oracle Rd.	0.67	7.00	6.33
Nogales Highway / Valencia Rd.	9.33	6.50	-2.83
Oracle Rd. / Prince Rd.	11.33	13.00	1.67
Oracle Rd. / River Rd.	1.67	4.00	2.33
Oracle Rd. / Wetmore Rd.	1.00	5.50	4.50
Speedway Blvd. / Stone Ave.	6.67	5.00	-1.67
Speedway Blvd. / Swan Rd.	1.67	1.50	-0.17
Speedway Blvd. / Wilmot Rd.	4.00	6.00	2.00
Speedway Blvd. / Interstate 10	3.00	1.50	-1.50
St. Mary's Rd. / Interstate 10	4.67	1.50	-3.17
Swan Rd. / 22nd St.	14.33	2.50	-11.83
Valencia Rd. / 12th Ave.	6.67	6.00	-0.67
Wetmore Rd. / First Ave.	2.33	2.50	0.17
Wilmot Rd. / 5th St.	4.00	4.50	0.50
Wilmot Rd. / 22nd St.	13.00	14.50	1.50
Interstate 10 / 22nd St.	4.00	2.50	-1.50
5th Ave. / Interstate 10	1.67	1.00	-0.67
Total	339.66	330.00	-9.66
Percent Change			-2.84%

Table 4-7. Left-Turn Accident Rate, City of Tucson Arterial / Arterial Intersections

Intersection	Left Turn Accident Rate *	
	1982 - 1984	1986 - 1987
Ajo Way / Mission Rd.	0.453	0.485
Ajo Way / Interstate 19	0.000	0.000
Ajo Way / 12th Ave.	0.593	0.344
Alvernon Way / Broadway Blvd.	0.337	0.186
Alvernon Way / 22nd St.	1.444	0.748
Broadway Blvd. / Campbell Ave.	0.292	0.836
Broadway Blvd. / Country Club Rd.	0.330	0.382
Broadway Blvd. / Craycroft Rd.	0.258	0.203
Broadway Blvd. / Kolb Rd.	0.236	0.198
Broadway Blvd. / Swan Rd.	0.266	0.222
Broadway Blvd. / Wilmot Rd.	0.376	0.145
Campbell Ave. / Fort Lowell Rd.	0.704	0.528
Campbell Ave. / Grant Rd.	0.320	0.373
Campbell Ave. / Speedway Blvd.	0.467	0.429
Congress St. / Granada Ave.	0.098	0.134
Congress St. / Interstate 10	0.921	0.704
Country Club Rd. / Grant Rd.	0.198	0.339
Country Club Rd. / Speedway Blvd.	0.184	0.191
Country Club Rd. / Valencia Rd.	0.158	0.311
Craycroft Rd. / Golf Links Rd.	0.158	0.508
Craycroft Rd. / 22nd St.	0.660	0.712
Fort Lowell Rd. / Oracle Rd.	0.056	0.461
Golf Links Rd. / Kolb Rd.	0.294	0.439
Golf Links Rd. / Wilmot Rd.	0.557	0.629
Grant Rd. / Oracle Rd.	0.456	0.502
Grant Rd. / Stone Ave.	0.442	0.421
Grant Rd. / Swan Rd.	0.546	0.380
Grant (Kolb) Rd. / Tanque Verde Rd.	0.659	0.736
Grant Rd. / First Ave.	0.333	0.172
Grant Rd. / Interstate 10	0.047	0.464
Kolb Rd. / Speedway Blvd.	0.463	0.358
Kolb Rd. / 22nd St.	0.767	0.590
Main Ave. / Speedway Blvd.	0.332	0.227
Miracle Mile / Oracle Rd.	0.036	0.372
Nogales Highway / Valencia Rd.	0.867	0.629
Oracle Rd. / Prince Rd.	0.594	0.671
Oracle Rd. / River Rd.	0.083	0.210
Oracle Rd. / Wetmore Rd.	0.056	0.281
Speedway Blvd. / Stone Ave.	0.657	0.498
Speedway Blvd. / Swan Rd.	0.078	0.095
Speedway Blvd. / Wilmot Rd.	0.185	0.293
Speedway Blvd. / Interstate 10	0.325	0.148
St. Mary's Rd. / Interstate 10	0.422	0.157
Swan Rd. / 22nd St.	0.725	0.129
Valencia Rd. / 12th Ave.	0.461	0.463
Wetmore Rd. / First Ave.	0.305	0.233
Wilmot Rd. / 5th St.	0.256	0.340
Wilmot Rd. / 22nd St.	0.556	0.625
Interstate 10 / 22nd St.	0.316	0.182
5th Ave. / Interstate 10	0.179	0.116

* Accidents per million entering vehicles

Table 4-8. Left-Turn Accidents, City of Tucson Arterial / Collector Intersections

Intersection	Number of Left Turn Accidents	
	1982 - 1984	1986 - 1987
Alvernon Way / 29th St.	29	14
Auto Mall Dr. / Oracle Rd.	1	3
Broadway Blvd. / Columbus Blvd.	13	3
Broadway Blvd. / Randolph Way	11	7
Broadway Blvd. / Rosemont Blvd.	5	3
Cherry Ave. / 22nd St.	11	11
Columbus Blvd. / 22nd St.	26	8
Grant Rd. / Wilmot Rd.	7	11
Limberlost Rd. / First Ave.	5	4
Oracle Rd. / Roger Rd.	6	1
Santa Clara Ave. / Valencia Rd.	7	2
Tucson Blvd. / Valencia Rd.	16	14

Table 4-9. Left-Turn Accidents per Year, City of Tucson Arterial / Collector Intersections

Intersection	Left Turn Accidents Per Year		
	Before	After	Difference
Alvernon Way / 29th St.	9.67	7.00	-2.67
Auto Mall Dr. / Oracle Rd.	0.33	1.50	1.17
Broadway Blvd. / Columbus Blvd.	4.33	1.50	-2.83
Broadway Blvd. / Randolph Way	3.67	3.50	-0.17
Broadway Blvd. / Rosemont Blvd.	1.67	1.50	-0.17
Cherry Ave. / 22nd St.	3.67	5.50	1.83
Columbus Blvd. / 22nd St.	8.67	4.00	-4.67
Grant Rd. / Wilmot Rd.	2.33	5.50	3.17
Limberlost Rd. / First Ave.	1.67	2.00	0.33
Oracle Rd. / Roger Rd.	2.00	0.50	-1.50
Santa Clara Ave. / Valencia Rd.	2.33	1.00	-1.33
Tucson Blvd. / Valencia Rd.	5.33	7.00	1.67
Total	45.67	40.50	-5.17
Percent Change			-11.32%

Table 4-10. Left-Turn Accident Rate, City of Tucson Arterial / Collector Intersections

Intersection	Left Turn Accident Rate*	
	1982 - 1984	1986 - 1987
Alvernon Way / 29th St.	0.502	0.351
Auto Mall Dr. / Oracle Rd.	0.017	0.073
Broadway Blvd. / Columbus Blvd.	0.159	0.058
Broadway Blvd. / Randolph Way	0.273	0.236
Broadway Blvd. / Rosemont Blvd.	0.118	0.12
Cherry Ave. / 22nd St.	0.211	0.347
Columbus Blvd. / 22nd St.	0.489	0.233
Grant Rd. / Wilmot Rd.	0.126	0.263
Limberlost Rd. / First Ave.	0.161	0.175
Oracle Rd. / Roger Rd.	0.183	0.042
Santa Clara Ave. / Valencia Rd.	0.216	0.079
Tucson Blvd. / Valencia Rd.	0.474	0.652

* Accidents per million entering vehicles

PART III

TRAFFIC OPERATIONS STUDIES

PART III of this report discusses the effort undertaken to determine the differences in traffic operation between leading left turn phasing and lagging left turn phasing.

CHAPTER 5 discusses the various intersection delay studies that were conducted in the Phoenix area. The first comparison made is that between leading and lagging operation operating at six intersections in the Phoenix area. From the analysis it is shown that total intersection delay is significantly greater with lagging left turns. The second comparison is between leading and combination operation at one intersection in Mesa. Due to the small sample size, a statistical test cannot be performed here. The third comparison is between Third Car and First car actuation operating at five intersections in the Phoenix area. These comparison showed no significant difference in total intersection delay, but a significant increase in left turn delay for the 3rd car actuated condition.

CHAPTER 6 discusses the signal operation analysis performed in the Pima County area. Leading left turn operation was compared to lagging left turn operation at actuated-isolated-unsaturated signals in the Pima County area. In a comparison in percent stopped vehicles, there is no change between leading and lagging operation. Vehicle delay increased at all intersections.

CHAPTER 7 discusses the travel time and delay studies that were performed in the Phoenix area. In Glendale and Tempe, nine routes were studied with four different timing plans - Existing all-leading, optimized all-leading, optimized all-lagging, and optimized combination. Leading and lagging were not permitted in opposing directions due to the trap situation. The results show no consistent result in the operation of these various patterns. In Mesa, however, leading left turn phasing was compared to leading eastbound, lagging westbound phasing. This phasing is different in that these phases are protected only and leading and lagging were permitted in opposing directions. The result of the Mesa study showed that delay, travel time and stops were all reduced with the combination phasing, although not significantly.

CHAPTER 5

PHOENIX AREA INTERSECTION ANALYSIS

INTRODUCTION

Intersection stopped time delay studies were conducted to evaluate the difference in performance between leading and lagging left turn arrow operation. One intersection was studied to evaluate the difference between leading and combination leading and lagging operation. Delay studies were also conducted, as part of this research, to evaluate the difference between 3rd car and 1st car actuation. The 3rd car/1st car comparison was performed strictly for the leading operation.

DATA COLLECTION

The study of comparisons took the form of a before and after analysis, therefore special care was taken to insure similar conditions existed for each study performed at a particular intersection. The duration of each study was one hour during the PM peak. Each study was conducted in good weather under normal traffic conditions. Measurement of intersection delay was performed by direct observation of stopped vehicles counted at fifteen second intervals. One observer was assigned to each approach. A turning movement volume count was performed for each study. Vehicles were counted as they entered the intersection. Volume count summaries were generated for each 15 minute interval.

The average stopped time delay was calculated using the equation:

$$\text{DELAY} = (\Sigma V_i * 15) / V$$

where:

DELAY = average delay, in seconds/vehicle;
 ΣV_i = sum of stopped vehicle counts;
15 = interval between stopped vehicle counts, in seconds; and
V = total volume observed during the study period.

Average stopped time delay values were calculated for left turn vehicles, through/right turn vehicles, and total intersection approach vehicles. Summary worksheets for each delay study are presented in Appendix D.

The following is a discussion on each of the comparisons that were made.

ANALYSIS

Leading Versus Lagging Operation

A paired comparison was made between the average delay per vehicle in the leading condition and the average delay per vehicle in the lagging condition. Six intersections were used in the analysis:

- 51st Avenue/Glendale,
- 51st Avenue/Northern,

- 51st Avenue/Olive,
- 51st Avenue/Peoria,
- 48th Street/Southern, and
- 48th Street/Broadway.

Manual stopped time delay studies were conducted at each intersection prior to any signal timing changes associated with this research. In the before condition, each of the six intersections operated with leading left turns. Five of the six intersections operated with protected/permissive left turn phasing and third car actuation on all approaches. The 48th St./Broadway intersection operated with protected only left turns and first car actuation on the northbound and southbound approaches and protected/permissive left turn phasing with third car actuation on the eastbound and westbound approaches.

Manual stopped time delay studies were conducted at each intersection with lagging operation. All approaches which were protected/permissive in the leading condition were permissive/protected in the lagging condition. The two protected only approaches remained protected only in the lagging operation.

Results

A before and after difference in the average stopped time delay per approach vehicle was calculated for each intersection. A difference was calculated for left turn vehicles, through/right turn vehicles, and total intersection approach vehicles. The percent change in delay from the before to the after condition was also calculated. The results of the Phoenix area intersection analysis of leading versus lagging left turn operation are presented in Table 5-1 and Figures 5-1, 5-2, and 5-3.

Average stopped time delay per left turn approach vehicle increased in the after condition at four of the six intersections studied. The largest change occurred at 51st Ave./Northern, where delay increased by 139% for left turn vehicles. The 48th St./Southern intersection measured essentially no change for left turn vehicle delay with the conversion to lagging left turns, while the intersection of 48th Street/Broadway registered a 5% decrease in delay for left turn vehicles in the after condition.

Average delay per through/right turn approach vehicle increased at five of the six intersections studied. The largest increase occurred at 48th St./Southern, with 129% more delay for through/right turn vehicles in the after condition. The 51st Ave./Northern intersection was the only intersection which registered a decrease in delay for through/right turn vehicles in the after condition. Delay decreased approximately 16% at this location.

Average delay per total approach vehicle also showed increases in the after condition at the same five intersections, though the changes were not as drastic when total intersection approach vehicles were considered. The large increase in through/right turn delay at 48th St./Southern was partially offset by no change in left turn delay. However, this intersection still registered the largest increase (85%) in total intersection delay with the conversion to a lagging operation. The 51st Ave./Northern intersection was the only location which registered an overall improvement in the after condition with a decrease in total intersection delay of approximately 4%.

Table 5-1. Leading vs. Lagging Intersection Delay, Phoenix Area

Intersection		Delay per Approach Vehicle (sec/veh)		
		Left Turn	Thru/Right	Total
1. 51st Ave/Glendale	Before	25.70	22.55	22.95
	After	57.79	34.34	37.66
	Difference	32.09	11.79	14.71
	Change	125%	52%	64%
2. 51st Ave/Northern	Before	23.51	44.57	41.57
	After	56.24	37.32	39.80
	Difference	32.73	-7.25	-1.77
	Change	139%	-16%	-4%
3. 51st Ave/Olive	Before	27.50	21.58	22.41
	After	45.30	27.65	30.19
	Difference	17.80	6.07	7.78
	Change	65%	28%	35%
4. 51st Ave/Peoria	Before	42.03	20.07	22.88
	After	65.64	33.83	38.00
	Difference	23.61	13.76	15.12
	Change	56%	69%	66%
5. 48th St/Southern	Before	54.95	21.56	27.23
	After	54.92	49.28	50.30
	Difference	-0.03	27.72	23.07
	Change	-0%	129%	85%
6. 48th St/Broadway	Before	63.39	39.27	44.51
	After	60.14	43.97	47.91
	Difference	-3.25	4.70	3.40
	Change	-5%	12%	8%
Analysis				
	Sample Size	6	6	6
	Mean of Difference	17.16	9.47	10.38
	Overall Change	63.30%	45.54%	42.17%
	Sample Standard Deviation	15.62	11.58	9.00
	Test Statistic (t)	2.691	2.002	2.825
	Significant @ 95%?	yes (p=.04)	no (p=.10)	yes (p=.04)

Before Condition: Leading Operation
 After Condition: Lagging Operation

Statistical Analysis

Three statistical tests were performed:

- a difference by intersection left turn movements,
- a difference by intersection through/right turn movements, and
- a difference by total intersection delay.

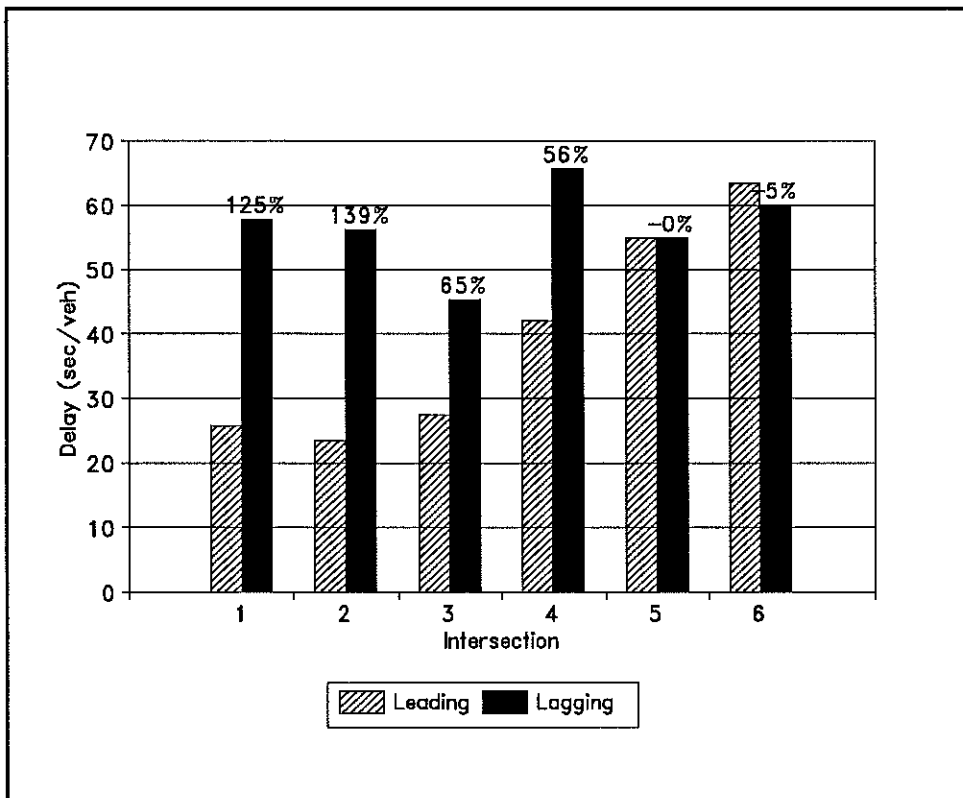


Figure 5-1. Leading vs. Lagging Left Turn Delay, Phoenix Area

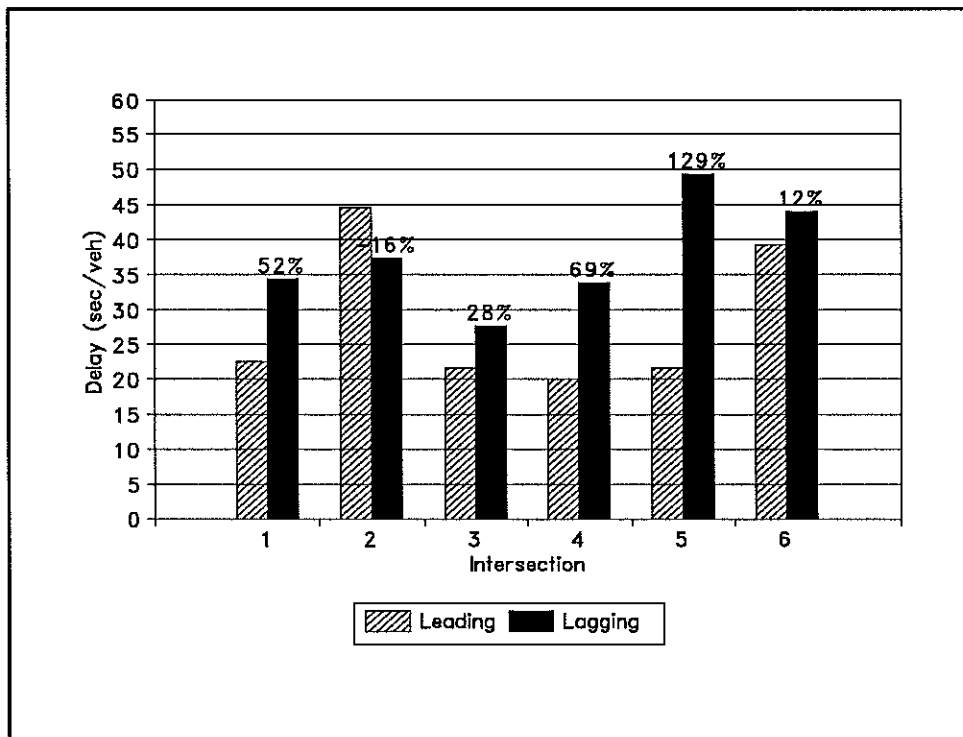


Figure 5-2. Leading vs. Lagging Through/Right-Turn Delay, Phoenix Area.

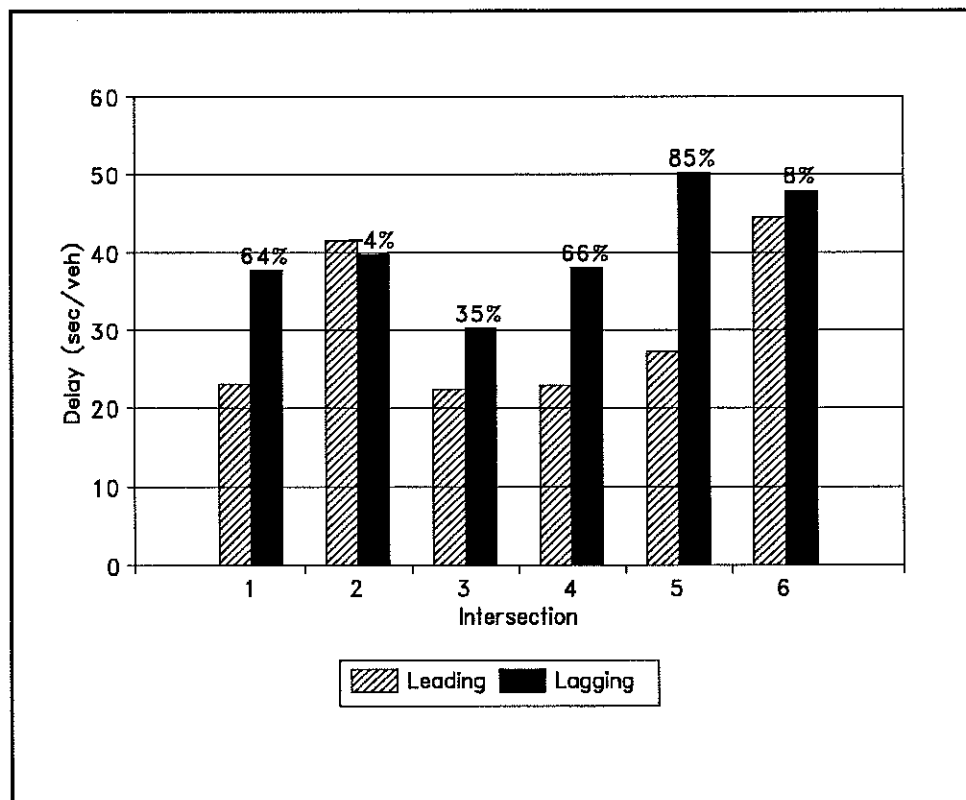


Figure 5-3. Leading vs. Lagging Total Intersection Delay, Phoenix Area

In each case, the statistical test performed was a paired t-test using the difference for each pair as one observed value. A mean of the difference was then calculated. The null hypothesis for the each test was that the difference between the before and after condition is equal to zero. Or, in other words, there is no significant difference in delay for the two conditions. A two tail test was performed at a 95% level of confidence.

The results of the paired data analysis are also presented in Table 5-1. The critical t-value for the test is 2.571. The mean of the difference for left turn vehicles is 17.16 seconds per approach vehicle. This represents an overall increase of 63% in delay with the conversion from a leading to a lagging operation. The calculated t-value is 2.691 ($p=.04$). The calculated t-value is greater than the critical t-value therefore the test indicates a statistically significant change in delay at the 95% confidence level for left turn vehicles. The mean of the difference for through/right turn vehicles is 9.47 seconds per approach vehicle, or an increase of approximately 46% in delay. The calculated t-value is 2.002 ($p=.10$). The calculated t-value is less than the critical t-value therefore the null hypothesis can not be rejected at the 95% confidence level on the basis of this test. The mean of the difference for total intersection delay is 10.38 seconds per approach vehicle, or an overall increase in total intersection delay of 42% with the conversion from leading to lagging left turn phasing. The calculated t-value is 2.825 ($p=.04$). The calculated t-value is greater than the critical t-value therefore the null hypothesis is rejected. On the basis of this test, it is concluded that total intersection delay is significantly greater for the lagging left turn operation.

Leading Versus Combination Operation

Two delay studies were performed at the intersection of Southern Ave./Stewart in Mesa to compare the difference in delay for a leading operation and a combination leading and lagging operation. Southern Avenue is an east/west arterial street. Stewart is a local collector street. The signal operated in a five phase mode in the before condition with protected only phasing on the east and west approaches. The combination phasing operated with leading left turns in the eastbound direction and lagging in the westbound direction. The signal was also operated in the protected only mode in the after condition.

Results

The results of the before and after study are presented in Table 5-2 and Figure 5-4. Delay per intersection left turn approach vehicle decreased by 4.61 seconds, or approximately 12%, in the after condition. The decrease was 1.13 seconds per vehicle for the through/right turn movements. This represents a change of approximately 11%. Total intersection delay decreased by 1.32 seconds per approach vehicle in the after period. Total intersection delay decreased by approximately 9% with the conversion to a combination leading and lagging operation.

This intersection was not included in the leading versus lagging analysis because of the different

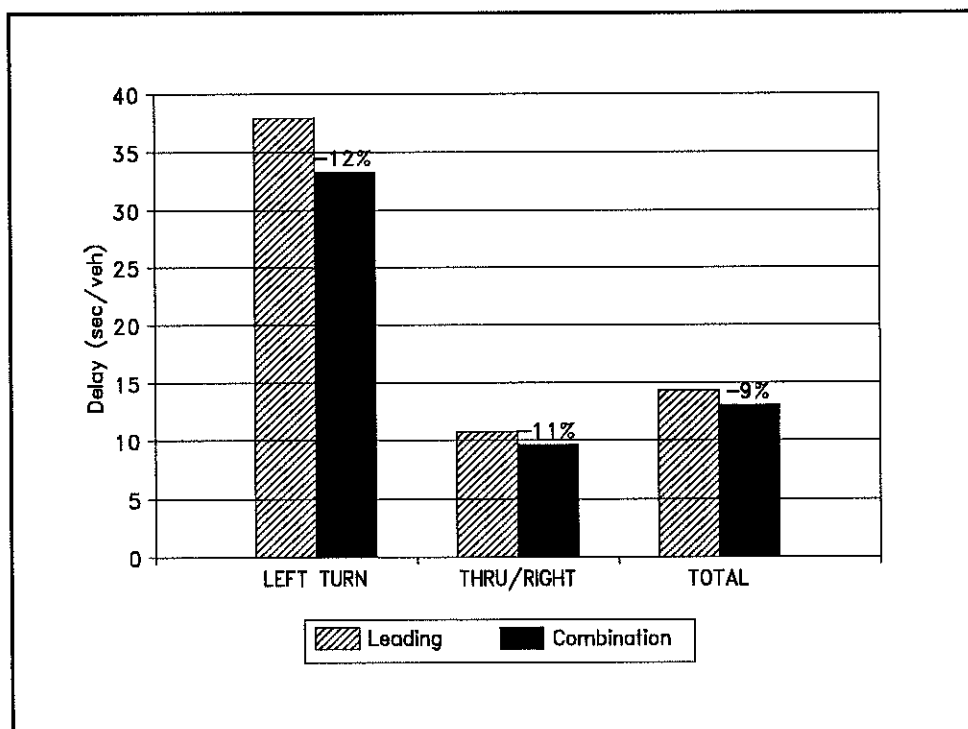


Figure 5-4. Leading vs. Combination Delay, Phoenix Area.

Table 5-2. Leading vs. Combination Intersection Delay, Phoenix Area

Intersection		Delay per Approach Vehicle (sec/veh)		
		Left Turn	Thru/Right	Total
Southern/Stewart	Before	37.86	10.76	14.34
	After	33.25	9.63	13.02
	Difference	-4.61	-1.13	-1.32
	Change	-12%	-11%	-9%
Before Condition:		Leading Operation		
After Condition:		Combination (leading EB/lagging WB)		

phasing pattern. A separate statistical analysis was not performed due to the limited sample size. The primary motivation for this study was to evaluate possible improved progression rather than intersection delay. The results of the progression analysis are included in Chapter 7 - Phoenix Area Travel Time Analysis.

Third Car Versus First Car Actuation

A paired comparison was also made between the average delay per vehicle in the 3rd car actuated condition and the 1st car actuated condition. Five intersections were used in the analysis:

- 48th Street/Southern,
- 48th Street/Broadway,
- 35th Avenue/Dunlap,
- 43rd Avenue/Northern, and
- 51st Street/Elliot.

Manual stopped time delay studies were conducted at each intersection prior to any signal timing changes associated with this research. In the before condition, all five intersections operated with leading left turns. Three of the five intersections operated with protected/permissive left turn phasing and 3rd car actuation on all approaches. The 48th Street/Broadway intersection operated with protected only left turns and 1st car actuation on the northbound and southbound approaches. The eastbound and westbound approaches operated with protected/permissive left turn phasing and 3rd car actuation. The 51st Street/Elliot intersection operated in a five phase mode in the before condition with protected/permissive left turn phasing and 3rd car actuation on the eastbound and westbound approaches.

Manual stopped time delay studies were conducted at each intersection with 1st car actuation. All approaches which were 3rd car actuated in the before condition were converted to 1st car actuation in the after condition. The two protected only approaches remained protected only with 1st car actuation in the after condition.

Results

A before and after difference in the average stopped time delay per approach vehicle was calculated for each intersection. A difference was calculated for left turn vehicles, through/right turn vehicles, and total intersection approach vehicles. The percent change in delay from the before to the after condition was also calculated. The results of the Phoenix area intersection analysis of 3rd car versus 1st car left turn actuation are presented in Table 5-3 and Figures 5-5, 5-6, and 5-7.

Average stopped time delay per left turn approach vehicle decreased in the after condition at four of the five intersections studied. The largest decrease occurred at 48th St./Southern, where delay decreased by approximately 32% for left turn vehicles. The 51st St./Elliot intersection recorded a 9% increase in delay for left turn vehicles in the after condition.

Table 5-3. Third Car vs. First Car Intersection Delay, Phoenix Area

Intersection		Delay per Approach Vehicle (sec/veh)		
		Left Turn	Thru/Right	Total
1. 48th St/Southern	Before	54.95	21.56	27.23
	After	37.43	27.66	29.35
	Difference	-17.52	6.10	2.12
	Change	-32%	28%	8%
2. 48th St/Broadway	Before	63.39	39.27	44.51
	After	50.56	31.46	35.78
	Difference	-12.83	-7.81	-8.73
	Change	-20%	-20%	-20%
3. 35th Ave/Dunlap	Before	35.51	30.63	31.25
	After	26.07	29.95	29.48
	Difference	-9.44	-0.68	-1.77
	Change	-27%	-2%	-6%
4. 43rd Ave/Northern	Before	39.95	39.17	39.27
	After	28.19	41.74	40.06
	Difference	-11.76	2.57	0.79
	Change	-29%	7%	2%
5. 51st St/Elliot	Before	29.41	9.55	14.72
	After	31.97	11.11	16.34
	Difference	2.56	1.56	1.62
	Change	9%	16%	11%
Analysis				
Sample Size		5	5	5
Mean of Difference		-9.80	0.35	-1.19
Sample Standard Deviation		7.51	5.17	4.47
Test Statistic (t)		-2.918	0.150	-0.597
Significant @ 95%?		yes (p=.04)	no (p=.89)	no (p=.58)
Before Condition:		3rd Car Actuated Leading Operation		
After Condition:		1st Car Actuated Leading Operation		

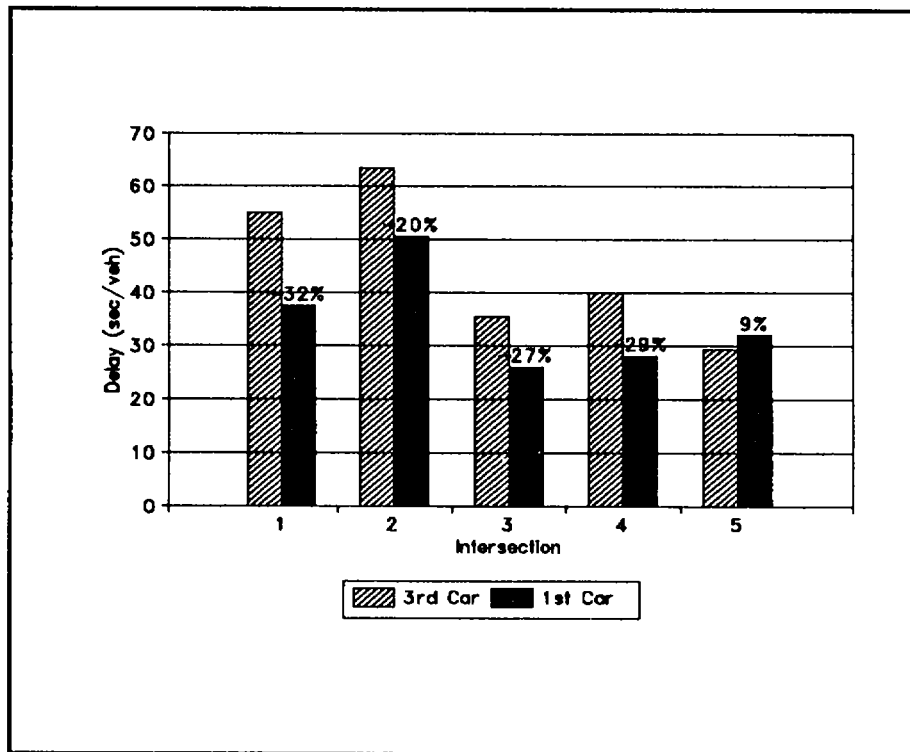


Figure 5-5. Third Car vs. First Car Left Turn Delay, Phoenix Area

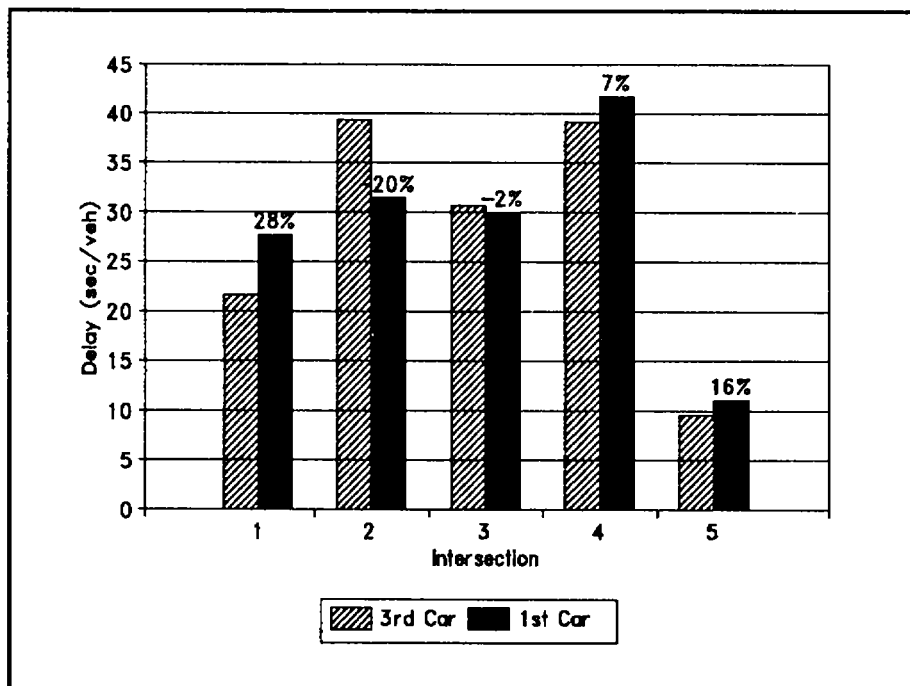


Figure 5-6. Third Car vs. First Car Through/Right-Turn Delay, Phoenix Area

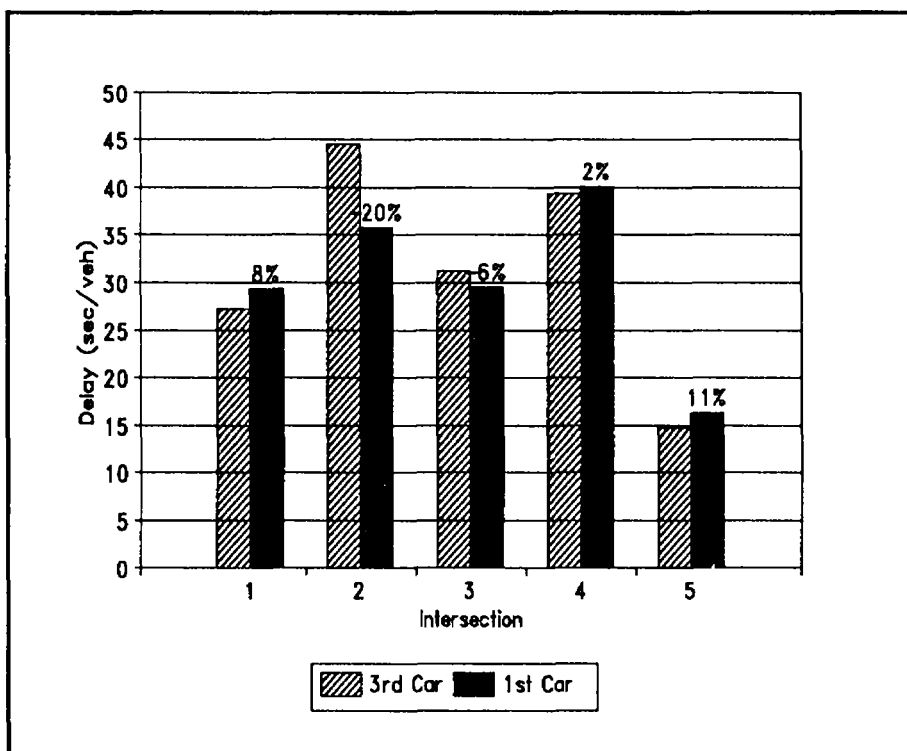


Figure 5-7. Thlrd Car vs. First Car Total Intersection Delay, Phoenix Area

Average delay per through/right turn approach vehicle increased at three of the five intersections studied. The largest increase occurred at 48th St./Southern with a difference of 6.1 seconds per approach through/right turn vehicle. This represents an increase in delay of approximately 28%. Two intersections actually show a decrease in delay for through/right turn vehicles with the conversion to 1st car actuation. The largest decrease occurred at 48th St./Broadway which recorded 7.81 seconds less delay or a decrease of 20% in the after condition.

Average delay per total intersection approach vehicle increased at three of the five intersections studied. The largest percent increase occurred at 51st St./Elliot where delay increased 11% with the conversion to 1st car actuation. The largest overall increase in delay occurred at 48th St./Southern where total intersection delay increased 2.12 seconds per approach vehicle in the after condition. This represents an increase in delay of 8% with the conversion to 1st car actuation. A decrease in total intersection delay occurred at two intersections. Delay decreased approximately 20% at 48th St./Broadway and approximately 6% at 35th Ave./Dunlap.

Statistical Analysis

The same three statistical tests used in the leading versus lagging analysis were performed to evaluate the difference in delay per vehicle for 3rd car and 1st car actuation. The null hypothesis, once again, is that there is no significant difference in delay for the two conditions. A two tail test was performed at a 95% level of confidence.

The results of the paired data analysis are also presented in Table 5-3. The critical t-value for the test is 2.776. The mean of the difference for left turn vehicles is -9.80 seconds per approach vehicle. The calculated t-value is -2.918. ($p=.04$) The absolute value of the calculated t-value is greater than the critical t-value therefore the test indicates a statistically significant decrease in delay at the 95% confidence level for left turn vehicles with 1st car actuation. The mean of the difference for through/right turn vehicles is 0.35 seconds per approach vehicle. The calculated t-value is 0.150 ($p=.89$). The calculated t-value is less than the critical t-value therefore the null hypothesis can not be rejected on the basis of this test. The mean of the difference for total intersection delay is -1.19 seconds per approach vehicle. The calculated t-value is -0.597 ($p=.58$). The absolute value of the calculated t-value is less than the critical t-value therefore the null hypothesis cannot be rejected. On the basis of this test, it is concluded that total intersection delay is not significantly different at the 95% level in the before and after conditions although there is a significant difference in delay for left turn vehicles.

DISCUSSION OF RESULTS

The results of the leading versus lagging analysis in the Phoenix area indicate a leading operation tends to be more efficient in terms of intersection delay. This finding is somewhat contrary to other experiments documented in the literature (10) However, the results of this current study are not surprising given the current phasing practices for implementation of lagging left arrow operations in the State of Arizona. In this research there were no left turn phase overlaps with the lagging left turn operations. Therefore, the potential benefits associated with phase overlap were lost in the conversion to a lagging operation.

The results of the leading versus combination lead/lag phasing indicate there may be reduced intersection delay with a combination phasing. However, the limited scope of the investigation precludes making any strong conclusions regarding the merits of combination phasing as related to intersection delay.

The results of the 3rd car versus 1st car actuation are perhaps the most interesting results associated with the Phoenix area intersection delay studies. As might be expected, the delay for left turn vehicles was less with 1st car actuation. However, the 51st St./Elliot intersection did record a 9% increase in delay for left turn vehicles in the after condition. However, this intersection does not provide a left turn phase for the north and south approaches. Therefore, the conversion to 1st car actuation did not serve as an advantage for left turners on the north and south approaches.

More surprising, however, were the results recorded for the through/right turn and total intersection delay. The analysis indicates no statistically significant difference at the 95% confidence level in delay per through/right turn vehicle or total approach vehicle with the change to 1st car actuation. This finding may, perhaps, be explained by examining the conditions under which the delay studies were performed.

The 48th St./Broadway intersection recorded a 20% decrease in intersection delay with the conversion to 1st car actuation. This intersection operates very close to capacity during the PM peak. The intersection also recorded slightly higher volumes during the 3rd car actuation study. This increased volume could have pushed the intersection into cycle failure during the course of the 3rd car actuation study.

All the delay studies were performed during the PM peak hour. Five intersections were used in the 3rd car versus 1st car analysis, or a total of 20 left turn approaches. All the intersections used in the analysis were running between 30 and 45 cycles per hour. Left turn volumes exceeded 150 vehicles per hour at 15 of the 20 approaches during the 3rd car actuated studies. These volumes would indicate the left turn arrow is being actuated a large proportion of cycles in the PM peak regardless of 1st car or 3rd car actuation.

The City of Phoenix collected data on the number of left arrow actuations and left turn volumes during the time the intersections of 35th Ave./Dunlap, 43rd Ave./Northern, and 51st St./Elliot were operated in the 1st car actuated mode. The same information was also collected for a typical weekday under 3rd car actuation. The data does indicate an increase in the number of times the arrow is actuated with the conversion to 1st car detection. However, the proportional increase in the number of actuation is much more acute in the off-peak hours than during the PM peak. Therefore, greater delay reductions should be expected in the off-peak rather than the PM peak with 3rd car actuation.

CHAPTER 6

PIMA COUNTY TRAFFIC SIGNAL OPERATION ANALYSIS

INTRODUCTION

As part of this project, an operational analysis of selected intersections in Pima County was undertaken. This analysis involved an examination of traffic and signal operation parameters before and after the conversion from leading to lagging turns. The purpose of this chapter is to document the data collection, analysis, and results of the study.

In 1984, the City of Tucson initiated a program to convert exclusive left turn signal phases from leading to lagging operation. The actual conversion of the signal phases began in 1985. Basically, the general rationale for this change was attributed to the potential for improving the operation of the signalized intersections with exclusive left turn phases. More specific reasons were related to:

- the need for the exclusive turn phase only when the demand in a signal cycle exceeded the capacity of the permitted left turn movement, and
- the influence of the leading left turn on arterial progression.

Given the conversion of the traffic signal operation by the City of Tucson, there was some lack of uniformity in the left turn phasing because the traffic signals under the jurisdiction of the Arizona Department of Transportation and the Pima County Department of Transportation continued to use the leading left turn phase. In order to eliminate the confusion to the motorists, all governmental agencies subsequently converted to the lagging left turn phase when exclusive turn phases are used. The Pima County Department of Transportation converted to the lagging left turn type of operation in the spring and summer of 1987.

The conversion from leading to lagging left turn signals by Pima County in 1987 represented a unique opportunity to examine the effect of the operational change. The time schedule for the conversion prevented the development of a formal funded research program on short notice; however a cooperative data collection effort was organized by Dr. Robert H. Wortman. With the cooperation of the Pima County Department of Transportation and the Arizona Department of Transportation, a "before and after" data collection effort was undertaken at selected intersections. This data set was then used as the basis of the comparative analysis of the left turn phasings in this research study.

Selection of Intersections

The conversion program in Pima County involved a total of thirty-seven signalized intersections in the Tucson area. At some of these intersections, various modifications to the signal operations were made in addition to the conversion of the left turn phasing. At a limited number of intersections, the only planned change was to switch from the leading to the lagging left turn operation; thus these intersections were selected for the "before and after" data collection. The intersections studied are listed in Table 6-1.

Ultimately, the intersection of First Avenue and Ina Road had other changes in the signal phasing

Table 6-1. Delay Study Intersections, Pima County

Intersection	Type of Control (a,b)
Ajo Way / Alvernon Way	4 Phase (c)
Alvernon Way / Irvington Rd.	4 Phase (Protected/Permissive)
Campbell Ave. / Skyline Rd.	3 Phase (Protected)
First Ave. / Ina Rd.	4 Phase (d)
First Ave. / Orange Grove Rd.	3 Phase (Protected/Permissive)
First Ave. / River Rd.	3 Phase (Protected/Permissive)
Ina Rd. / Thornydale Rd.	4 Phase (Protected/Permissive)
Kolb Rd. / Valencia Rd.	4 Phase (Protected)
Palo Verde Rd. / Valencia Rd.	3 Phase (Protected)

(a) The number of phases reflects the basic operation of the intersection. Phase overlaps were used in situations with opposing leading protected left turns.

(b) In the "after" condition, the "protected / permissive" left turn operation obviously becomes "permitted / protected".

(c) At the intersection of Ajo Way and Alvernon Way, a combination of types of control were used. For example, some approaches had protected left turn operations.

(d) At the intersection of First Avenue and Ina Road, a 4-phase signal operation was used in the before condition with protected / permissive left turns on the northbound and westbound approaches. For the after condition, the northbound and southbound approaches on First were treated as separate phases. In addition, the lane use on the northbound approach was changed.

as well as modifications in the lane use. While field data were collected at the site, the intersection was eliminated from the comparative analysis for this reason. In addition, the initiation of construction in the area of Ina Road and Thornydale Road significantly changes the traffic at that location prior to an opportunity to collect the "after" data.

While the changes in signal phasing at these intersections were limited to the conversion of the left turn operations, it must be recognized that there were some modifications in the signal timing. These modifications included the adjustment of green time allocation for specific movements as well as a re-evaluation of the time for the clearance or change interval.

Signal Phasing

Pima County uses actuated control for traffic signals; thus all of the intersections in the study utilized full actuated control. In addition, each of the intersections operated on an isolated basis with no interconnection with adjacent signals.

There was some variation in the treatment of left turn movements in the study intersections. Some of the intersections had permitted plus protected left turn movements while other intersections had protected left turn movements only. Table 6-1 identifies the operation of the left turn signal phasings at each of the study locations.

As has been indicated previously, the intersection of First Avenue and Ina Road ultimately underwent changes in signal operation as well as lane use. These modifications significantly changed the operation of the intersection; thus the intersection was later eliminated from the analysis.

It should be noted that phase overlaps were used for the leading left turn conditions; however, the overlaps were not used with the lagging left turn operations. For example, given an intersection with left turn arrows on all approaches, the signal would operate as an eight phase signal (or four phase with phase overlaps for the turn movements) with the leading left turns. With the lagging left turns, the signal would operate as four phase control (without any overlaps). This type of operation was standard in the Tucson area. In essence, this resulted in the loss of the use of the phase overlap when there were differences in the demand for the left turn movement.

At a limited number of intersections which utilized the protected only left turns, a phase overlap condition would occur with the lagging left turn operation. For example, one intersection had very low westbound approach volumes. For some cycles, the eastbound through and left turn movements would occur at the same time. At another intersection, the side street had low volumes on the north and south approaches. In addition, the westbound approach had very few left turns. Because of the lack of westbound left turns and cycles without traffic on the side street, the eastbound through movement continued along with the eastbound protected left turn. In essence, there was no need for a protected westbound left turn phase in some cycles. This type of operation only occurred at intersections with protected only left turn operations.

With respect to the actual signal timing, the study utilized the signal settings employed by Pima County for the before and after conditions. There was no attempt by the research team to evaluate the signal timing settings used at the intersections. Certainly, it was necessary for Pima County to adjust some of the signal timing settings in addition to changing from the leading to the lagging operation. Part of the reason for the necessity of adjusting the signal timings was associated with the fact that the loss of the left turn phase overlap had an impact on the phasing for the through movements.

DATA COLLECTION

For the field data collection, two time lapse super 8mm movie cameras were used to film the operation of each of the intersections. The location of the cameras was elevated by using trucks with elevating platforms or raised vantage points from nearby terrain. With the use of two cameras, it was possible to simultaneously film all of the intersection approaches. In addition, the cameras had internal clocks with digital displays; thus the filming with the two cameras could be coordinated. All filming was accomplished with the cameras operating on a speed of one frame per second.

The filming of each intersection occurred during the period from 3 PM to 6 PM on weekday afternoons. There was an attempt to schedule the before and after data collection at a specific intersection on the same day of the week even though all intersections were not filmed on the same day of the week. While filming was scheduled for the period from 3 PM to 6 PM, it was not possible to obtain a three hour data set in all cases. Equipment problems in addition to the time required to change the film cartridges resulted in some lost time.

The time period from 3 PM to 6 PM was selected for several reasons. First, this period permitted making observations over a peak hour period. Second, it was possible to schedule the use of the trucks with elevating platforms at the end of the normal workday. Finally, it was difficult to schedule personnel for data collection at other times. While it may have been desirable to collect data at other time periods, it must be recognized that the data collection was accomplished with resource

limitations on a cooperative basis. Nevertheless, a rather extensive data set was collected for study.

The before data were collected during the period from middle of March 1987 to the middle of May 1987. This time schedule was necessitated and constrained by the timing of the signal conversions by Pima County. The after data collection began in early October 1987; thus there was a transition period of several months before the collection of the after data. During the fall of 1987, difficulties were encountered which served to disrupt and extend the data collection effort. For example, adverse weather and other demands for the use of the trucks made it impossible to film on some days. In addition, the shortening of the daytime period finally made it necessary to cease the data collection efforts until the spring of 1988. Data collection resumed in the spring of 1988. Difficulties were encountered with the films taken at the intersection of Kolb Road and Valencia Road; thus data collection was repeated at that intersection during the summer of 1990.

ANALYSIS

Using the film record of the intersections during the before and after periods, data which reflected operational parameters were extracted. This operational data for each intersection was then used for the comparative analysis of the leading and lagging left turn phasing. The discussion that follows presents the analysis and results of each of the operational parameters.

Intersection Volume

In the design of the data collection effort, it was recognized that significant changes in volume can have a potential impact on the operational measures of intersection performance. For this reason, a number of precautions were taken in an attempt to minimize the possibility of major changes in volume between the before and after study periods. For example, the initiation of the data collection for the after period was undertaken within several months of the completion of the before data collection. The after data collection was delayed until the fall of 1987 to avoid the possible effect of the summer period. In addition, an effort was made to collect the before and after data at a given intersection on the same day of the week.

The turn movement volumes for each intersection were obtained from the film records for the before and after periods. These volumes were then used to determine the actual changes in approach volumes for the two study periods.

Because of the loss of some time during the data collection process, the raw turn movement volumes were expanded to the equivalent of a three hour period. The total volume was then divided by three to provide an average hourly volume. This procedure resulted in a number that could be used for comparing the before and after periods. Table 6-2 presents the average approach volumes for each intersection.

At most of the study intersections, only minor differences in traffic volumes were observed. Given a relatively short period between the before and after data collection, only small differences would be expected.

Table 6-2. Intersection Total Approach Volumes, Pima County

Intersection	Average Approach Volume (vph)*		
	Before	After	Difference
Ajo Way / Alvernon Way	3644	3523	-3%
Alvernon Way / Irvington Rd.	2788	2882	3%
Campbell Ave. / Skyline Rd.	2527	3070	21%
First Ave. / Orange Grove Rd.	2519	2472	-2%
First Ave. / River Rd.	3379	3107	-8%
Ina Rd. / Thornydale Rd.	3495	**	**
Kolb Rd. / Valencia Rd.	7052	5950	-16%
Palo Verde Rd. / Valencia Rd.	2560	2472	-3%

* The average approach volumes are for the entire intersection. The value in the table reflects the sum of all approaches.

** After values not available for Ina Rd. / Thornydale Rd.

Two exceptions to small changes in the approach volumes can be noted. The intersection of Campbell Avenue and Skyline Drive, however, had a significant increase in traffic volume for which there is no explanation for the cause. The before data set was collected in April 1987, and the after data set was taken the following October. While there was only six months between the data collection periods, there was a 21 percent increase in the approach volumes at that intersection. This increase generally occurred on all approaches and throughout the study period. In essence, there was a major increase in the use of the intersection.

In the second case, there was a 16 percent decrease in the approach volumes at the intersection of Kolb Road and Valencia Road. At this location, there had been a major change in employment in the vicinity of this intersection; thus the after condition was influenced by the reduction in employment.

In terms of later analyses of operational performance, it should be noted that significant increases in traffic volumes were found at only one intersection. In most cases, there was a reduction in the approach volumes.

Arrival of Vehicles

In addition to approach volume, the actual time of arrival of vehicles at an intersection during the signal cycle has an influence on overall performance measures. For this reason, the arrival of vehicles was examined as part of the analysis of before and after conditions.

All of the intersections in the study were operating on an isolated control basis. While there may be some platooning from adjacent signals, the overall arrival pattern should be random in terms of the time that vehicles arrive during a cycle.

The arrival pattern of vehicles for a given intersection was examined by determining the percent of the approach vehicles that had to stop due to the operation of the traffic signal. Basically, the review

of the film revealed the approach vehicles that were required to stop as well as the vehicles that were able to pass through the intersection without stopping. The percent vehicles stopped was then calculated by comparing the number of vehicles that stopped to the total approach volume. Table 6-3 summarizes this information for each of the intersections.

A review of Table 6-3 reveals that there was little change in the percent vehicles stopped at half of the intersections. There was increase of about five percent in the stopping vehicles at one intersection, and a decrease of about six percent at another. The greatest measured change was at the intersection of Kolb Road and Valencia Road where there was an increase of ten percent. This difference was based on only the east and west intersection approaches.

Another interesting aspect of the information in Table 6-3 is the consistency of the values for the various intersections. At most of the intersections the percent of stopped vehicles was in the general range of fifty to fifty-five percent. The main exception was the intersection of Palo Verde Road and Valencia Road where the percentage for the before and after conditions was significantly lower than at other intersections. This lower value can be explained by the fact that there is a free flow right turn lane on one of the approaches.

Vehicle Delay

One of the main indicators of intersection performance is vehicle delay. Delay is specified in the *Highway Capacity Manual* (12) as the measure for determining intersection level of service. For this study, the stopped time delay was determined for each of the intersections. The standard procedure for determining stopped delay was used where the number of stopped vehicles is counted at a set interval. The intersections were filmed at one second intervals; thus the delay was determined based on observations taken from the film. While it is common to select fifteen second intervals for observations, a ten second interval was used in this study. The shorter interval was used to improve the accuracy especially for the movements with low approach volumes.

Table 6-4 summarizes the results of the delay analysis and indicates the average stopped delay for the stopped vehicles as well as the total approach vehicles. These values reflect the overall delay for

Table 6-3. Percent of Approach Vehicles Stopped, Pima County

Intersection	Percent Stopped	
	Before	After
Ajo Way / Alvernon Way	54.1	53.0
Alvernon Way / Irvington Rd.	54.5	53.8
Campbell Ave. / Skyline Rd.	50.7	55.6
First Ave. / Orange Grove Rd.	55.6	49.5
First Ave. / River Rd.	54.4	55.7
Ina Rd. / Thornydale Rd.	60.6	*
Kolb Rd. / Valencia Rd.	60.1**	70.4**
Palo Verde Rd. / Valencia Rd.	31.3	33.3

* After value not available for Ina Rd. / Thornydale Rd.

** At the Kolb Rd. / Valencia Rd. intersection, the values are for the eastbound and westbound approaches only. For the before condition, the percent vehicles stopped for all approaches was 49.2 percent. The after condition value for all approaches was not available.

Table 6-4. Vehicle Delay Comparison, Pima County

Intersection	Delay per Stopped Vehicle (Sec)	Delay Per Approach Vehicle (Sec)
Ajo Way / Alvernon Way		
Before	32.68	17.75
After	39.68	21.04
Difference	7.00 (21%)	3.29 (19%)
Alvernon Way / Irvington Rd.		
Before	22.82	12.44
After	32.32	17.39
Difference	9.50 (+42%)	4.95 (+40%)
Campbell Ave. / Skyline Dr.		
Before	27.45	13.93
After	31.43	17.47
Difference	3.98 (+14%)	3.54 (+25%)
First Ave. / Orange Grove Rd.		
Before	22.88	12.72
After	27.11	13.43
Difference	4.23 (+18%)	0.71 (+6%)
First Ave. / River Rd.		
Before	32.15	17.48
After	33.55	18.68
Difference	1.40 (+4%)	1.20 (+6%)
Ina Rd. / Thornydale Rd.		
Before	33.03	20.01
After	*	*
Difference		
Kolb Rd. / Valencia Rd.		
Before	26.04	12.69
After	*	19.27
Difference		6.58 (+52%)
Palo Verde Way / Valencia Rd.		
Before	19.25	6.03
After	23.58	7.85
Difference	4.33 (+22%)	1.82 (+30%)
Average Change	+20%	+30%

* After value not available

an intersection. More detailed information for each approach and the movement at each approach is contained in Appendix E. At all of the intersections where delay was actually measured, there were increases in the average delay per vehicle. Even for the intersections where there were decreases in the approach volume, the average vehicle delay increased.

In considering the results of the delay analysis, it is important to recognize that the data collection was during the period from 3 PM to 6 PM. For this reason, a true off peak condition was not included in the analysis.

Cycle Length

The final parameter that was included in the analysis of the before and after conditions was cycle length. Again, it should be noted that the research team did not attempt to evaluate the adequacy of the signal timing. The study simply utilized the signal timings that were in place prior to and after the conversion of the left turn signal operation. Upon the implementation of the lagging left turn signals, the Pima County staff did make some adjustments in the signal timing. These adjustments were necessary for the efficient operation of the intersection.

The average signal cycle lengths for the before and after periods for each intersection are given in Table 6-5. A general review of the table reveals that the differences in the cycle lengths vary from intersection to intersection with increases at some of the sites and decreases at other locations. If the differences in cycle length are considered in terms of the type of left turn treatment, there is a trend that can be noted. At intersections where there was a decrease in the cycle length, the permitted/protected left turn was utilized. The increases in cycle length were at intersections where protected only left turns were utilized. Changes in cycle length, therefore, were a function of whether left turns were permitted along with the through movement or not.

The exception to an increase in cycle lengths with protected only lagging left turns occurred at the intersection of Palo Verde Rd. and Valencia Rd. At this intersection, the average cycle lengths remained virtually the same even with the protected left turn operations. Because of the low approach volumes for some movements, this is one of the intersections that resulted in a phase overlap type of operation. Because of this condition, the average cycle length remained the same.

Table 6-5. Average Cycle Length, Pima County

Intersection	Average Cycle Length (Sec)		
	Before	After	Difference
Ajo Way / Alvernon Way	95.3	114.3	19.0
Alvernon Way / Irvington Rd.	72.6	70.4	-2.2
Campbell Ave. / Skyline Rd.	79.9	90.3	10.4
First Ave. / Orange Grove Rd.	77.3	71.9	-5.4
First Ave. / River Rd.	95.6	90.7	-4.9
Ina Rd. / Thornydale Rd.	85.8	*	
Kolb Rd. / Valencia Rd.	65.7	76.7	11.0
Palo Verde Rd. / Valencia Rd.	62.1	62.6	0.5

* After value not available for Ina Rd. / Thornydale Rd.

DISCUSSION OF RESULTS

In considering the results of the analysis of the Pima County intersections, it must be recognized that:

- all of the study locations were operating with actuated control;
- the signals were basically isolated from other intersections, and there was no coordination with adjacent intersections at the time of the data collection;
- the intersections were not operating at what could be considered as saturated conditions; and
- vehicle queues generally cleared during each cycle.

There was some variation in the measured approach volumes at the study intersections; however only major changes occurred at two intersections. Because the intersections were not operating at saturated conditions, increases in volumes would not necessarily result in significant increases in delay.

Generally, there was little change in the percent vehicles stopped. This would suggest that arrival pattern was random in terms of the signal cycle. For this reason, the effect of platooning should not be a factor with respect to delay calculations and measurements.

It is significant to note that the reduction in cycle length was associated with intersections where permitted left turns were allowed. On the other hand, intersections with protected left turns only had increases in cycle length with the lagging left turn operation. This result is reasonable because of the fact that the opportunity for phase overlap was lost when the lagging left turn was used. In considering this general statement, it must be recognized that low traffic volumes for some movements can result in phase overlap operations with lagging protected only left turns. For this type of condition, the average cycle length did not increase.

The interesting result of the analysis is that vehicle delay increased at all intersections. At the study intersections, there was an average increase of 20% in the delay per stopped vehicle and an average increase of 30% in the delay per approach vehicle. The finding of delay increases is consistent with the results of the Phoenix area studies. Even when there was a decrease in approach volumes, there were increases in delay. Delay might be expected to increase with longer cycle lengths; however delay also increased at intersections with reductions in average cycle length.

CHAPTER 7

TRAVEL TIME STUDY

INTRODUCTION

As part of this research project alternative phasing sequences were tested using travel time data along five routes in Glendale and four routes in Tempe. The patterns tested were:

- All Leading
- All Lagging
- A combination of leading or lagging depending on which best fit the progression.

In addition, a combination phasing was tested along Southern Avenue in Mesa. This chapter documents the timing, data collection, analysis, and results of these travel time studies.

SIGNAL TIMING

In order to obtain a true comparison between leading and lagging left turns, it was necessary to use signal timing patterns developed by a common optimization program. Because of the ease of operation and the numerous runs that would be required as part of the combination portion of the study, FORCAST was utilized to optimize the signals. The first signal timing - all leading left turns, was performed using FORCAST operating on the City of Scottsdale computer. Subsequent runs were performed on the PC-based version of the FORCAST program.

Initial travel time runs were performed along each route to determine travel speeds and link distances. Existing intersection phasing and minimum times were obtained from the City of Glendale and City of Tempe Traffic Engineering staff. Traffic volumes were obtained from the city staff and the Maricopa Association of Governments Transportation Planning Division and were supplemented with turning movement counts made by Lee Engineering.

FORCAST optimizes by calculating a cost for each cycle length. A range of acceptable cycle lengths is input into the program. Based upon the phasing, volumes, and progression priority, FORCAST creates an optimum timing plan for each cycle length. FORCAST then calculates the motorists' cost of each timing plan based upon the main street delay, side street delay, and stops. A stop is equivalent to 20 seconds of either main street or side street delay. FORCAST uses a simple procedure to increase the cost due to a saturated intersection. If the intersection is saturated, FORCAST adds one cycle length to both the main street and side street delay value.

Timing plans were implemented in the study area for AM peak, PM peak and off-peak traffic patterns. Since FORCAST allows for different phasing patterns, the coding and optimization of all leading or all lagging was straightforward. The most difficult part of the timing portion of the project was in determining which combination of lead and lag at each intersection would produce the optimum combination timing.

For the Glendale timing, at each intersection along 51st Avenue there are 16 timing combinations theoretically possible as listed in Table 7-1.

Table 7-1. Travel Time Study Possible Signal Combinations, Phoenix Area

Combination	Approach			
	North	South	East	West
1	Lead	Lead	Lead	Lead
2	Lead	Lead	Lead	Lag
3	Lead	Lead	Lag	Lead
4	Lead	Lead	Lag	Lag
5	Lead	Lag	Lead	Lead
6	Lead	Lag	Lead	Lag
7	Lead	Lag	Lag	Lead
8	Lead	Lag	Lag	Lag
9	Lag	Lead	Lead	Lead
10	Lag	Lead	Lead	Lag
11	Lag	Lead	Lag	Lead
12	Lag	Lead	Lag	Lag
13	Lag	Lag	Lead	Lead
14	Lag	Lag	Lead	Lag
15	Lag	Lag	Lag	Lead
16	Lag	Lag	Lag	Lag

If the four signals along 51st Avenue could be timed with any of the sixteen timing patterns, then in order to determine the optimum phasing combination at each intersection, timing plans would have to be generated for $16^4=65,536$ possible combinations. If there are three timing patterns- AM, MID, and PM, possible, the number jumps to $65,536 * 3 = 196,608$ possible combinations.

Since all of the signals along 51st Avenue operate in a protective-permissive mode, only four of the sixteen combinations can be utilized in order to avoid the trap. These four combinations are shown in Table 7-2.

This reduced the number of patterns in Glendale to 256 plans per time period or a total of 768 combinations. In Tempe only two signals were changed from leading to lagging requiring the generation of only 48 timing plans.

Table 7-2. Travel Time Study Utilized Signal Combinations, Phoenix Area

Combination	Approach			
	North	South	East	West
1	Lead	Lead	Lead	Lead
4	Lead	Lead	Lag	Lag
13	Lag	Lag	Lead	Lead
16	Lag	Lag	Lag	Lag

There was one additional constraint in that whatever combination was chosen, it had to be implemented for all three time periods of the day. Therefore if Peoria WB had lagging left turn in the AM peak, it had to remain that way for the off-peak and PM peak periods.

Once the timing plans were generated the outputs were scanned for the lowest cost cycle length. This was not necessarily the same cycle length for each combination. A spreadsheet was then created which showed each combination and the costs associated with the AM, PM and off-peak plan. This

Table 7-3. Lowest Cost Timing Plans, City of Glendale

Intersection Phasing				Weighted Cost			Total
Glendale	Olive	Peoria	Northern	AM	Mid	PM	
2	3	2	2	941	1820	2267	5028
2	2	2	2	924	1804	2313	5041
2	3	2	4	989	1838	2276	5103
2	2	2	4	972	1824	2322	5118
2	2	2	1	972	1827	2334	5133
2	3	2	3	1057	1840	2267	5165
2	2	2	3	1106	1826	2313	5245
2	3	4	2	1090	1948	2227	5265
2	3	4	3	1101	1969	2225	5295
2	3	3	2	1128	1821	2354	5302
2	2	3	2	1111	1806	2400	5316
2	2	3	2	1111	1806	2400	5317
2	3	4	4	1139	1968	2251	5357
2	3	3	4	1192	1840	2363	5395
1	2	2	2	943	1902	2552	5396
2	2	3	4	1175	1826	2409	5410
2	3	3	1	1192	1844	2374	5410
2	3	3	3	1219	1841	2354	5414
2	2	3	1	1175	1829	2420	5425
3	3	3	2	1134	1815	2501	5450
2	2	3	3	1235	1827	2400	5462
3	3	3	3	1184	1837	2501	5522
3	3	3	4	1198	1834	2510	5542
2	1	2	2	1068	1849	2639	5556
3	3	3	1	1198	1838	2522	5558
3	3	2	2	956	2246	2391	5592
2	1	2	4	1122	1868	2649	5639
2	1	2	1	1122	1872	2660	5654
2	1	2	3	1175	1870	2639	5684
2	1	3	2	1258	1851	2753	5862
4	3	4	4	1260	2355	2260	5874
2	1	3	3	1272	1872	2753	5897
2	1	3	4	1340	1870	2762	5972
2	1	3	1	1340	1874	2774	5988

Legend:

1 All Lagging

2 All Leading

3 Leading N-S Lagging E-W

4 Leading E-W Lagging N-S

was weighted by the volume to determine the lowest cost plan. The thirty lowest cost plans for Glendale are shown in Table 7-3 and the lowest cost plans for Tempe are shown in Table 7-4.

It should be noted that the lowest cost timing plan for both cities was very similar to the all-leading timing plan. There are two reasons this occurred. By implementing lagging left turns, these must be tied together preventing an overlap scenario. Since there is a loss of efficiency associated with this type of phasing, FORCAST will only choose lagging if the left turn volumes are nearly identical. If lagging left turns are implemented, the greatest benefit is that should the left turn vehicles make their maneuvers during the through movement, ie. finding available gaps in the traffic stream, then it is possible that the protected left turn phase will not be necessary. FORCAST does not have an algorithm which determines if this scenario will occur, therefore, it cannot recognize the benefits of lagging left turns. There may be situations where the left turn traffic volume is light but unbalanced and FORCAST would choose leading operation, while lagging might be a better choice both because it fits better in the progression scheme and because lagging operation might avoid the need for some of the protected phases, which provides more time for the through movement.

DATA COLLECTION

Once the timing plans were implemented into the street, travel time runs were performed using the 'floating car' method. The TIMELAPSE Travelog data collection computer was utilized to collect this data. Once the routes are entered into the computer, the driver simply pushes a button at the beginning of the route and drives to the end of the route.

Table 7-4. Lowest Cost Timing Plans, City of Tempe

Intersection Phasing		Weighted Cost			Total
Broadway	Southern	AM	Mid	PM	
3	3	820	971	444	2234
2	3	836	985	436	2258
3	2	820	1072	391	2282
4	2	832	1038	419	2288
1	2	820	1126	435	2382
1	3	826	1163	463	2451
4	3	836	1167	461	2465
2	4	836	1285	389	2510
2	1	831	1264	420	2515
4	4	816	1405	418	2639
3	1	801	1555	428	2783
4	1	833	1523	448	2805
1	4	809	1600	410	2819
3	4	861	1649	394	2904

Legend:

1 All Leading

2 All Lagging

3 Leading N-S Lagging E-W

4 Leading E-W Lagging N-S

Six travel time runs were performed for each route in each direction for three time periods - AM peak, PM peak, and off-peak. One driver collected all the data in Glendale and a separate driver collected the travel time data for Tempe. The same driver was used for all runs in each city in order to eliminate the variability of different drivers.

Once all of the travel time runs were collected, they were up loaded to ASCII files on the IBM PC. TIMELAPSE has developed a software program which reads these data files and computes the following information:

- Travel Time
- Time in Queue (delay time)
- Stops
- Average speed
- Cruise speed
- Fuel Consumption
- Carbon Monoxide emissions
- HydroCarbons emissions
- Nitrous oxides emissions

An example output for the software program is found in Appendix F.

The six runs were averaged for each route to determine the average stops, delay time and travel time for each route. Each of the estimates for the routes was multiplied by its respective volume to produce a weighted point estimate based upon the route volume. A paired Student's t-test was then performed between each sample. The following comparisons were made:

- Existing leading minus FORCAST optimized leading
- Existing leading minus FORCAST optimized lagging
- Existing leading minus FORCAST optimized combination
- FORCAST leading minus FORCAST lagging
- FORCAST leading minus FORCAST combination
- FORCAST lagging minus FORCAST combination

The estimates of stops, delay and travel time produce three distinct variables for each timing plan. In order to compare the timing plans, it was felt that aggregating these three variables into one variable would be helpful. Because FORCAST develops timing plans which weights the benefit of reduced stops with reduced delay and travel time, a representative cost for each timing plan was developed using the information in *A Manual on User Benefit Analysis of Highway and Bus Transit Improvements*, (13) published by the American Association of State Highway and Transportation Officials, 1977. These values have been updated to 1988 dollars by using the transportation portion of the Consumer Price Index. The following values were utilized.

<u>Parameter</u>	<u>Cost</u>
Stops	\$41.00 / 1000 stops
Delay	\$ 0.616 / Vehicle-hour idling
Travel Time	\$ 3.35 / Vehicle-hour traveling

ANALYSIS

Glendale Travel Time Study

The study area for the Glendale portion of the project was bounded by Grand Avenue to the south, Cactus Road to the north, 43rd Avenue to the east, and 67th Avenue to the west as shown in Figure 7-1. In this study area, all the major arterial - major arterial intersections were operating in a protected-permissive leading left turn mode in the before condition. Optimization of all of the signals within the study area was performed using the FORCAST signal timing program but only the signals along 51st Avenue had the phasing patterns changed during the course of the study.

The five routes chosen for the Glendale study were the following:

- 51st Avenue
- 59th Avenue
- Peoria Avenue
- Olive Avenue
- Northern Avenue

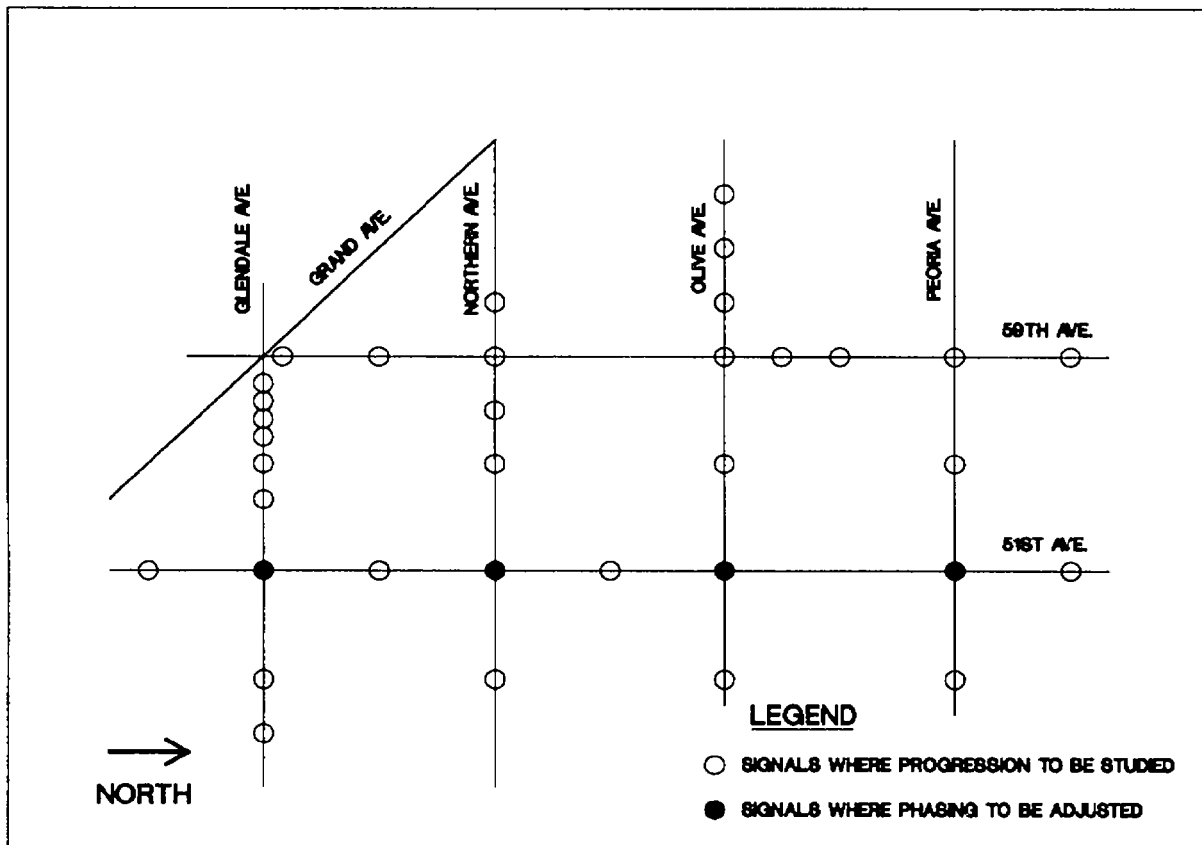


Figure 7-1. Lead-Lag Study Area, City of Glendale

Table 7-5. Travel Time Results, City of Glendale

Route and Time		Weighted Delay (Vehicle - Hours)				Weighted Travel Time (Vehicle Hours)				Weighted Stops (Thousand Vehicle-Stops)			
		Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.	Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.	Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.
51st Ave. NB	AM	7	45	26	42	124	162	143	157	2	6	6	5
51st Ave. NB	MID	20	25	25	12	180	188	186	169	3	3	8	3
51st Ave. NB	OFF	77	40	44	34	475	417	408	405	12	8	8	8
51st Ave. NB	PM	106	81	78	25	413	383	380	317	15	15	12	6
51st Ave. SB	AM	42	64	39	82	359	382	351	385	9	12	9	12
51st Ave. SB	MID	24	49	27	15	186	210	185	170	5	5	5	5
51st Ave. SB	OFF	54	25	22	38	466	426	409	446	12	8	8	8
51st Ave. SB	PM	14	79	90	84	210	285	289	277	6	10	12	10
59th Ave. NB	AM	6	24	19	29	97	115	105	117	3	4	4	5
59th Ave. NB	MID	19	13	17	14	143	131	135	135	3	2	3	3
59th Ave. NB	OFF	44	49	44	55	345	362	333	349	12	8	8	12
59th Ave. NB	PM	53	61	37	33	225	239	195	192	11	9	4	4
59th Ave. SB	AM	26	19	39	21	192	182	206	185	5	2	7	5
59th Ave. SB	MID	22	11	25	9	143	134	153	130	3	3	5	3
59th Ave. SB	OFF	45	43	24	28	320	323	281	297	11	7	7	11
59th Ave. SB	PM	9	37	38	37	92	131	127	123	2	6	6	6
Northern Ave. EB	AM	9	23	16	6	92	106	97	82	4	2	4	2
Northern Ave. EB	MID	14	35	24	16	99	122	105	98	4	5	4	4
Northern Ave. EB	OFF	12	46	20	29	206	230	199	209	4	4	4	4
Northern Ave. EB	PM	28	44	56	48	141	160	174	159	7	11	11	9
Northern Ave. WB	AM	12	48	30	37	98	130	113	119	4	4	4	6
Northern Ave. WB	MID	10	10	9	10	87	86	86	85	3	2	3	3
Northern Ave. WB	OFF	46	3	25	12	274	237	258	243	5	0	5	5
Northern Ave. WB	PM	63	62	29	24	195	186	146	144	11	8	3	5
Olive Ave. EB	AM	18	22	23	58	133	144	140	188	4	4	6	8
Olive Ave. EB	MID	34	18	3	7	176	157	138	136	7	2	2	2
Olive Ave. EB	OFF	52	63	15	8	334	347	286	274	10	10	5	5
Olive Ave. EB	PM	27	55	50	61	168	185	176	195	7	7	7	9
Olive Ave. WB	AM	10	44	29	26	102	150	119	118	2	7	3	2
Olive Ave. WB	MID	26	17	5	7	143	133	120	123	4	2	2	4
Olive Ave. WB	OFF	39	70	35	36	316	359	305	308	10	10	10	10
Olive Ave. WB	PM	70	51	60	34	257	213	226	194	12	6	12	6
Peoria Ave. EB	AM	8	14	9	10	44	50	44	44	1	2	2	1
Peoria Ave. EB	MID	20	7	12	8	114	98	100	99	4	2	2	2
Peoria Ave. EB	OFF	28	22	36	22	218	215	222	210	4	8	8	8
Peoria Ave. EB	PM	18	38	39	37	113	130	137	130	4	4	5	4
Peoria Ave. WB	AM	8	7	9	12	62	59	63	69	2	1	2	3
Peoria Ave. WB	MID	12	11	8	5	90	85	86	81	3	2	3	2
Peoria Ave. WB	OFF	36	35	33	31	219	217	212	211	8	8	8	4
Peoria Ave. WB	PM	11	31	48	46	122	147	161	161	5	5	7	5
Total:		1179	1440	1217	1146	7773	8015	7601	7536	242	222	235	219

The data from these five travel time runs are shown in Table 7-5. Comparisons were made between the different phasing patterns. The comparison between (1) existing leading (2) FORCAST optimized leading (3) FORCAST optimized lagging and (4) FORCAST optimized combination shown in Appendix D with the results shown in Table 7-6.

An equivalent cost/hour which shows an equivalent motorists' cost based upon stopped time delay, travel time and stops is shown in Figure 7-2. This information is broken into the four travel time periods AM peak, midday peak, PM peak, and an off-peak period.

As Table 7-6 suggests, there is a significant difference in travel time and delay between both the FORCAST leading - FORCAST lagging and between the FORCAST leading -FORCAST combination plans. There doesn't seem to be any discernible pattern. If the cost parameter alone is looked at, then it appears that the existing timing plan works best for the AM peak, the combination plan works best for the midday and PM peak, and the lagging plan works best for the off-peak. In the AM peak, the lagging plan also works better than the FORCAST leading or the combination.

It appears, at least from this information, that lagging left turns work best in situations such as an off peak period where left turn volumes are relatively light. In this instance, the extra time that is saved from sometimes avoiding the left turn phase can be given to the through movements resulting in better progression.

Table 7-6. Travel Time Study Comparisons, City of Glendale

Comparison	Least Delay	Level of Significance (p)	Least Travel Time	Level of Significance (p)	Least Stops	Level of Significance (p)
Existing Leading - FORCAST leading	Existing Leading	.07	Existing Leading	.16	FORCAST Leading	.27
Existing Leading - FORCAST lagging	Existing Leading	.08	FORCAST Lagging	.34	Existing Leading	.73
Existing Leading - FORCAST Combination	FORCAST Combination	.86	FORCAST Combination	.27	FORCAST Combination	.26
FORCAST Leading - FORCAST lagging	FORCAST Lagging	.03	FORCAST Lagging	.01	FORCAST Leading	.43
FORCAST Leading - FORCAST Combination	FORCAST Combination	.02	FORCAST Combination	.01	FORCAST Combination	.87
FORCAST Lagging - FORCAST Combination	FORCAST Combination	.47	FORCAST Combination	.58	FORCAST Combination	.29

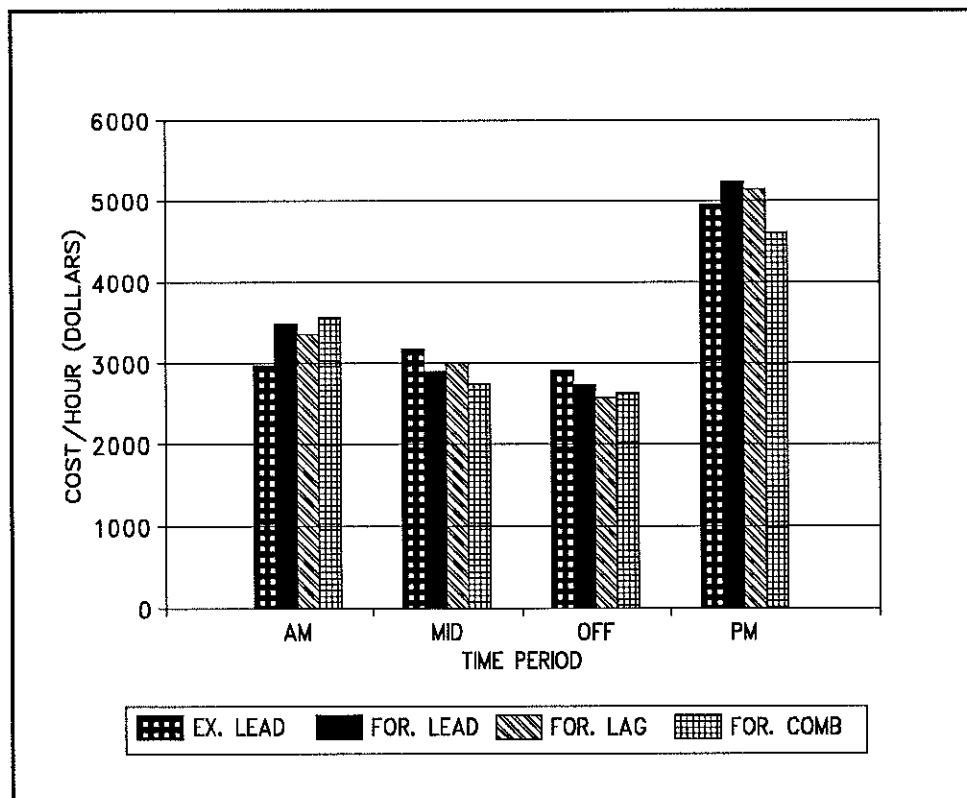


Figure 7-2. Travel Time Study Cost/Hour, City of Glendale

Tempe Travel Time Study

The study area for the Tempe analysis is bounded by Broadway Road to the north, Southern Avenue to the south, 48th Street to the west, and Hardy Drive to the east as shown in Figure 7-3. In this study area, all major arterial - major arterial intersections were operating in protected-permissive leading left turn operation with the exception of the north and south approaches at 48th Street and Broadway. Due to the dual left turns at these approaches they operate in a protected-only leading left turn mode. FORCAST was used to create timing plans for all signals within the study area, however alternate phasing were only implemented at 48th Street and Broadway and 48th Street and Southern.

The routes chosen for this study were the following:

- 48th Street
- Priest Drive
- Southern Avenue
- Broadway Road

The data from these travel time runs are shown in Table 7-7. Comparisons were made between the different phasing patterns. The comparison between (1) existing leading (2) FORCAST optimized leading (3) FORCAST optimized lagging and (4) FORCAST optimized combination is shown in Appendix D and the results from these comparisons are shown in Table 7-8.

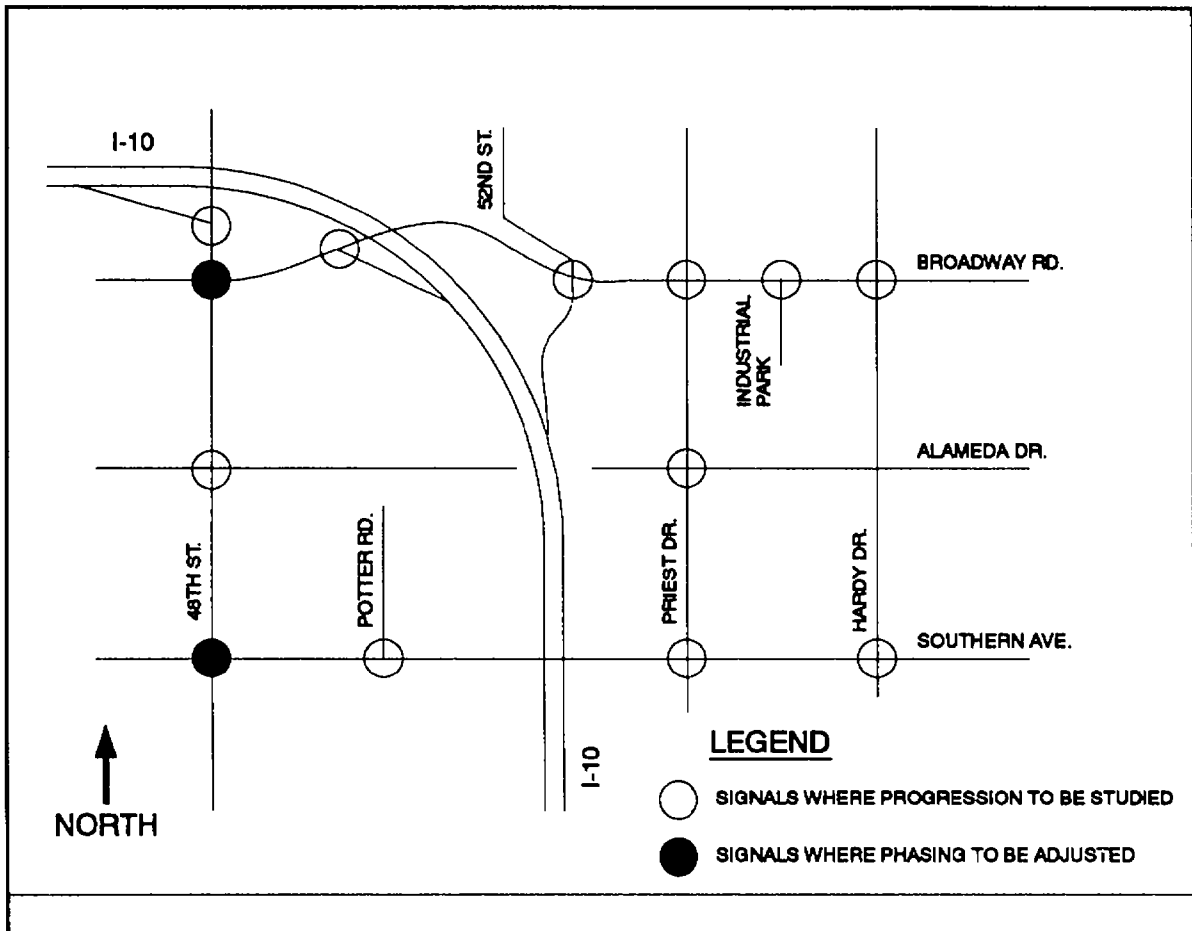


Figure 7-3. Lead-Lag Study Area, City of Tempe

An equivalent cost/hour which shows an equivalent motorists' cost based upon stopped time delay, travel time and stops is shown in Figure 7-4. This information is broken into the three travel time periods AM peak, midday peak and PM peak.

The results shown in Table 7-8 indicate that there is only one significant result in the Tempe travel time data. FORCAST leading had significantly fewer stops than FORCAST lagging.

In viewing Figure 7-4, it is noted that lagging has a higher cost than FORCAST leading or combination in the midday and PM peak, but combination has a higher cost in the AM peak. The cost difference between leading and lagging is least in the AM peak and greatest in the PM peak. In Tempe, at the two intersections where lagging left turns were implemented, there is a very great directional split between left turns at these two intersections in the PM peak. By forcing these two movements together, it has greatly increased the motorists' cost in the PM peak.

Table 7-7. Travel Time Results, City of Tempe

Route and Time		Weighted Delay (Vehicle-Hours)				Weighted Travel Time (Vehicle-Hours)				Weighted Stops (Thousand Vehicle-Stops)			
		Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.	Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.	Exist. Lead.	FOR. Lead.	FOR. Lag.	FOR. Comb.
48th St.. NB	AM	17	4	3	15	117	101	94	117	3	3	3	7
48th St.. NB	MID	28	4	8	38	164	141	142	176	5	5	5	5
48th St.. NB	PM	25	40	44	42	96	112	117	115	3	3	3	3
48th St.. SB	AM	5	36	22	14	48	79	66	58	1	3	3	4
48th St.. SB	MID	49	14	68	29	246	191	250	203	6	0	12	6
48th St.. SB	PM	44	11	87	48	202	157	239	184	14	5	14	5
Southern Ave. EB	AM	12	16	12	9	55	54	50	47	3	2	2	2
Southern Ave. EB	MID	26	N/A*	18	6	209	N/A*	197	168	9	N/A*	4	4
Southern Ave. EB	PM	54	63	21	5	241	237	199	167	13	9	4	4
Southern Ave. WB	AM	15	58	42	19	149	198	181	151	3	10	10	3
Southern Ave. WB	MID	11	N/A*	47	33	187	N/A*	229	207	0	N/A*	9	5
Southern Ave. WB	PM	23	17	27	13	103	96	104	89	6	2	2	4
Broadway Rd. EB	AM	6	15	14	23	104	110	109	119	2	2	2	7
Broadway Rd. EB	MID	49	106	167	49	483	540	598	466	21	10	21	10
Broadway Rd. EB	PM	22	117	68	120	271	358	310	359	6	17	17	17
Broadway Rd. WB	AM	30	52	34	38	202	208	205	204	12	4	8	8
Broadway Rd. WB	MID	117	72	52	57	550	481	458	467	21	10	10	10
Broadway Rd. WB	PM	100	43	137	79	283	201	301	236	12	4	12	8
Priest Rd. NB	AM	9	31	11	14	79	98	83	85	6	3	3	3
Priest Rd. NB	MID	17	6	3	31	161	149	150	170	6	6	6	11
Priest Rd. NB	PM	8	21	16	25	74	84	82	88	2	2	2	2
Priest Rd. SB	AM	1	4	22	21	34	35	56	53	1	0	1	1
Priest Rd. SB	MID	1	1	1	1	120	130	124	116	0	0	0	0
Priest Rd. SB	PM	19	11	6	16	113	99	99	107	3	3	3	3
Total (Minus Southern Mid)		652	741	865	706	3894	3859	4016	3777	151	104	146	126

* - Not able to collect data due to construction along Southern Ave.

Table 7-8. Travel Time Study Comparisons, City of Tempe

Comparison	Least Delay	Level of Significance (p)	Least Travel Time	Level of Significance (p)	Least Stops	Level of Significance (p)
Existing Leading - FORCAST leading	Existing Leading	.59	FORCAST Leading	.86	FORCAST Leading	.08
Existing Leading - FORCAST lagging	Existing Leading	.16	Existing Leading	.41	FORCAST lagging	.99
Existing Leading - FORCAST Combination	Existing Leading	.69	FORCAST Combination	.43	FORCAST Combination	.35
FORCAST Leading - FORCAST lagging	FORCAST Leading	.47	FORCAST Leading	.37	FORCAST Leading	..05
FORCAST Leading - FORCAST Combination	FORCAST Combination	.78	FORCAST Combination	.56	FORCAST Leading	.13
FORCAST Lagging - FORCAST Combination	FORCAST Combination	.26	FORCAST Combination	.12	FORCAST Combination	.23

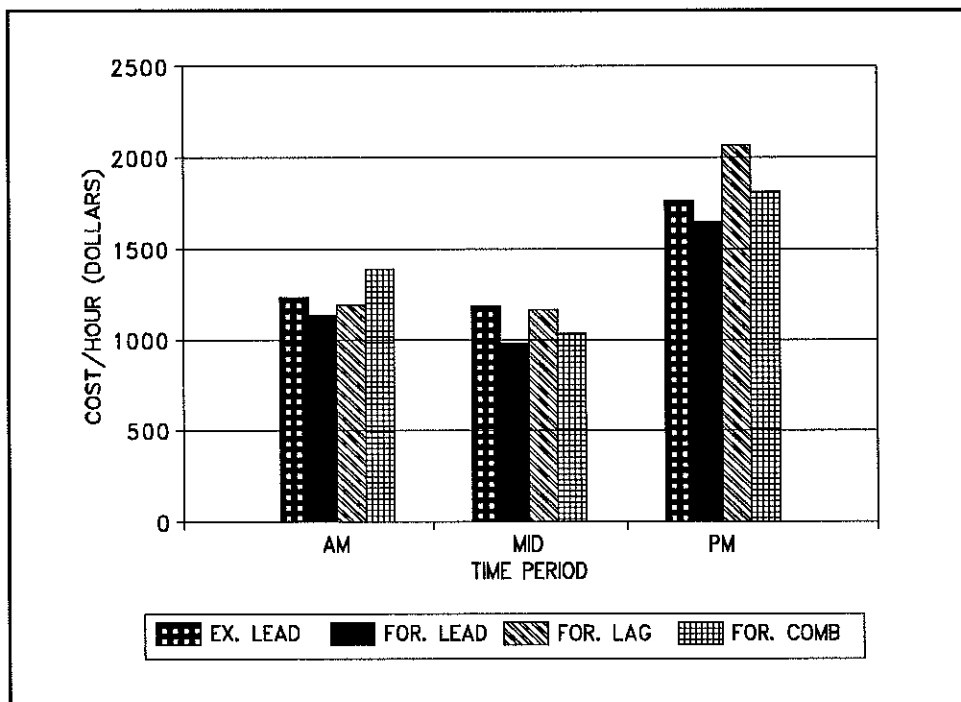


Figure 7-4. Travel Time Study Cost/Hour, City of Tempe

Mesa Travel Time Study

The City of Mesa changed the phasing at Southern and Stewart from Leading east-west to leading east and lagging west. This study area is shown in Figure 7-5. Lee Engineering collected travel time data along Southern Avenue in the AM, Midday and PM peak time periods to determine the effect of this changeover. The results of this change are shown on Table 7-9.

While not significant, these numbers do show a substantial reduction in delay, stops, and travel time due to the changing from an all leading phasing pattern to a combination leading-lagging phasing pattern.

Scottsdale Travel Time Study

In the Spring of 1988, Lee Engineering performed an optimization of the signals within the City of Scottsdale. Optimization was performed using the city's FORCAST computer program. At that time, several travel time runs were performed using the TIMELAPSE Travelog data collector to determine stops, delay, and travel time. These travel time runs were performed by members of the City Council, Transportation Commission and city staff.

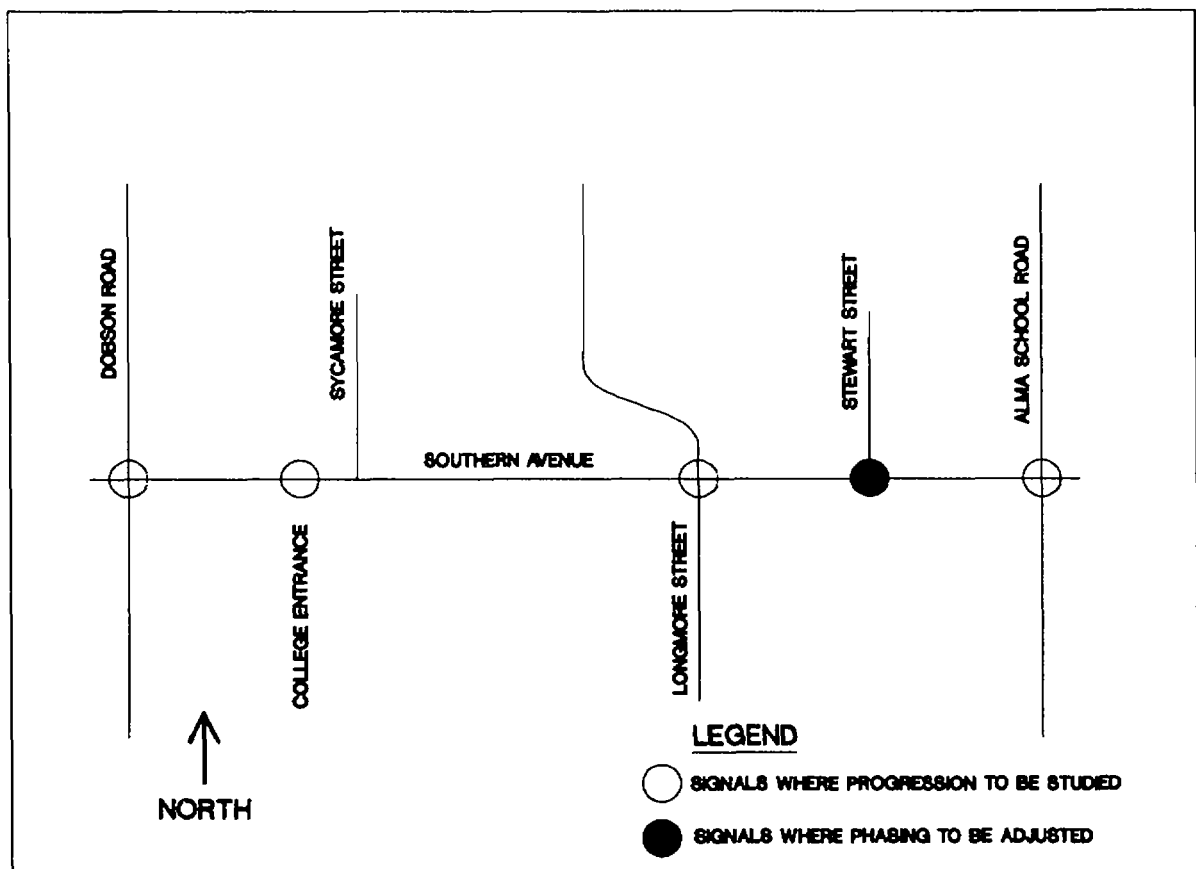


Figure 7-5. Lead-Lag Study Area, City of Mesa

Table 7-9. Travel Time Studies Leading Minus Combination, City of Mesa

Route	Time	Weighted Delay (Vehicle-hours)			Weighted Travel Time (Vehicle-hours)			Weighted Stops (Thousand Vehicle Stops)		
		Leading	Lagging	Difference	Leading	Lagging	Difference	Leading	Lagging	Difference
Southern Ave. EB	AM	5	0	5	27	22	6	0.8	0.0	0.8
Southern Ave. EB	MID	52	1	51	129	71	58	5.2	0.0	5.2
Southern Ave. EB	PM	41	8	33	132	90	42	5.9	2.9	2.9
Southern Ave. EB	AM	10	3	8	68	60	8	2.1	2.1	0.0
Southern Ave. EB	MID	5	5	0	76	74	2	2.4	2.4	0.0
Southern Ave. EB	PM	0	5	-5	74	66	8	0.0	2.5	-2.5
Total		113	21		506	382		16.4	10.0	
		Sample Size	6		Sample Size	6		Sample Size	6	
		Mean Difference	15.197		Mean Difference	20.579		Mean Difference	1.069	
		Std Deviation	21.871		Std Deviation	23.436		Std Deviation	2.675	
		Test Stat.	1.702		Test Stat.	2.151		Test Stat.	0.979	
		Significant	N		Significant	N		Significant	N	
		Level of			Level of			Level of		
		Significance (p)	.15		Significance (p)	.09		Significance (p)	.37	

Once the city converted all their signals to lagging phasing, city staff performed another retiming of their signal system in the Spring of 1990. Assuming the volumes along the streets stayed relatively constant over this two year period, another set of travel time runs were performed by city staff.

The results of the leading and lagging phasing is shown in Table D-4 in Appendix D. In some cases, the travel time studies for both the leading and lagging left turns were conducted at different times of the day, specifically the PM peak runs were made between 4 PM and 6 PM in 1988 and generally between 4 PM and 5 PM in 1990. The results shown in Figure F-1 (Appendix F-4) however, have been analyzed for both leading and lagging in those time periods which were common to both plans. This information must be used carefully for several reasons:

- 2 year time period between studies.
- City conversion of numerous intersections from protected to permissive -protected between the two studies.
- Reduction of extension time throughout system.
- Refinement of leading timing patterns after the before studies.
- More recent traffic counts in timing lagging condition.
- Different drivers in before and after studies.

DISCUSSION OF RESULTS

It is difficult to determine if either leading or lagging left turns are a better operation for a given situation. While not statistically significant, lagging left turns appeared to operate better for three time periods in Glendale (based on FORCAST plans).

The combination timing plan worked better than leading or lagging in Glendale for only the Midday and PM peak. In Tempe, the combination was never the lowest-cost plan. This was surprising, for it was felt that by having the opportunity for leading or lagging at a particular intersection would help improve progression. It should be stressed again that the FORCAST timing plan must overcome two obstacles in order to choose lagging left turns for intersection phasing. The fact that it does not recognize left turns made on the permissive period results in it not determining the true best combination plan.

The combination timing plan fared best in Mesa where stops, delay, and travel time were all three reduced substantially. This type of combination phasing is different than those tested in either Glendale or Tempe. The Mesa combination plan was leading eastbound and lagging westbound. In Tempe the phasing tested was leading north-south and lagging east-west. It would appear that a substantial reduction in motorist cost is not very apparent with this type of phasing, but is very apparent with the Mesa phasing. It is important to realize that to implement the Mesa phasing, it is necessary to have either protected only operation, or programmed visibility traffic signal heads as is currently being used in Texas.

In conclusion the following points should be mentioned.

- One of the greatest benefits of lagging left turns is in decreasing the need for a protected left turn phase. This increases the opportunity for larger progression bands through the intersection. In order for a timing program to implement the best phasing, it is necessary for that program to evaluate the left turn movement in conjunction with gaps in the opposing traffic stream. Since FORCAST does not do this, it is not a good program for optimizing the combination phasing. A program which evaluates the gaps in the opposing traffic stream would be a better program. It is likely that FORCAST may pick the wrong timing plans for an area when considering the combination of leading and lagging left turns.
- Combination timing seems to work best when leading and lagging are implemented for opposing directions, i.e. leading eastbound and lagging westbound. There does not appear to be much benefit when leading and lagging are implemented for perpendicular directions, i.e., lagging north-south and leading east-west. It is possible however, that the latter condition could result in improvement if the optimization software recognized the left turns made in a permissive manner.
- One benefit for lagging operation may be in locations where left turns are actuated by the first car in the left turn bay. Although this same benefit may be realized in some situations with third car actuation, there are those where sufficient gaps occur in the opposing traffic stream to permit more than two vehicles turning left on the permissive phase. In those cases, lagging would skip the protected phase and 3rd car actuated leading would not. Each time this occurs in a coordinated system, the time saved from omitting the protected phase goes to one of the

through green phases thereby increasing the opportunity for improved progression. But, the time saved by omitting the protected phase may be offset by increased delay to through traffic during the simultaneous protected phase when there are few, if any, left turn vehicles on the opposing approach.

- In locations like Tempe, where there is a high directionality with opposing left turn volumes, there is substantial delay associated with lagging operation due to the loss of phase overlap. At locations where lagging is implemented, programmed visibility signal heads might permit phase overlap with permissive-protected operation.

PART IV

PUBLIC PERCEPTION STUDIES

PART IV documents public opinion surveys which were conducted to determine if motorists have a preference for a leading or a lagging operation.

CHAPTER 8 examines the results of public opinion surveys conducted in the Cities of Glendale and Tempe. Both surveys were conducted by taking a random sample of motorists at intersections which had been converted, as part of this research, from leading to lagging left turn operations. The survey instrument chosen for this study was a mail-in questionnaire which contained four questions. The first two questions provided information concerning driver awareness of various left turn operations. The second two questions provided information concerning driver preference for leading or lagging left turn operations. There were 802 responses received from the Glendale questionnaire mailing and 633 from the Tempe mailing. Approximately 49% of the Glendale motorists which responded to the survey indicated the signals are better with leading left arrows, while approximately 42% preferred the lagging operation. The results of the Tempe questionnaire indicated a nearly two-to-one preference for the lagging left arrow operation. One possible reason Tempe motorists may prefer the lagging operation is the close proximity of Tempe and Scottsdale, where lagging left turns are utilized.

CHAPTER 8

PUBLIC AWARENESS AND PERCEPTION

INTRODUCTION

One of the important aspects of this research effort, especially from the perspective of an elected official, deals with the possible preference of either leading or lagging operation. Information concerning motorist preference of leading or lagging left turn operation was obtained through public opinion surveys conducted in the Cities of Glendale and Tempe. Both surveys were conducted by taking a random sample of motorists at intersections which had been converted, as part of this research, from leading to lagging left turn operations.

DATA COLLECTION

The survey instrument chosen for this study was a mail-in questionnaire. A questionnaire containing four multiple choice questions and a space for additional comments was prepared. The questionnaire was designed to be contained on a nine inch by four inch postage paid post card. A copy of the questionnaire used for motorists in the City of Tempe is shown in Figure 8-1. A similar questionnaire was prepared for the City of Glendale survey. The only difference between the two questionnaires were those changes which were necessary to reflect a change in study area location. A cover letter, which accompanied the questionnaire, briefly explained the nature of the study and the various types of left turn operation: leading, lagging, and combination leading and lagging. The first two questions provided information concerning driver familiarity with the study area and left turn operations. The second two questions provided information concerning driver perception of and preference for the various types of left turn operations examined in this research effort.

Two lists, each with 2400 recorded license plates, were generated. The first list was generated from the four intersections converted in the City of Glendale:

- 51st Ave./Glendale,
- 51st Ave./Northern,
- 51st Ave./Olive, and
- 51st Ave./Peoria.

The number of plates recorded was evenly distributed among the four intersections and among the four approaches at each intersection. Ten percent of the plates recorded were from left turning vehicles and 90% from through or right turning vehicles. The sample was also distributed throughout the day with 20% of the plates being recorded between 7:00 and 9:00 AM, 60% between 9:00 AM and 4:00 PM, and 20% between 4:00 and 6:00 PM.

The second list was generated from the two intersections converted in the City of Tempe:

- 48th St./Southern, and
- 48th St./Broadway.

QUESTIONNAIRE

Note: This questionnaire is a part of a research project designed to study traffic signal operation. Your response could help the City of Tempe and the Arizona Department of Transportation improve traffic flow. **Please Respond!** Recently the City of Tempe changed the left turn arrows at 48th Street and Broadway and 48th Street and Southern. There have been three types of left turn arrow operation:

- a. All leading left turn arrows (May, 1990 and before)
 - b. All lagging left turn arrows (early June, 1990)
 - c. Some leading and some lagging left turn arrows (late June, 1990)
1. How many times per week do you drive in this area?
☐ 0-5
☐ 6-10
☐ 11-15
☐ 16+
 2. Had you noticed this change in left turn arrows?
☐ yes ☐ no
 3. Please think about your past and present travel in this area.
When driving in this area, do you encounter:
☐ more green lights with all leading left turn arrows
☐ more green lights with all lagging left turn arrows
☐ more green lights with some leading and some lagging
☐ no difference
 4. With respect to left turns, are the signals:
☐ better with leading left turn arrows
☐ better with lagging left turn arrows
☐ no difference
 5. If one (leading or lagging) is better, why?

Figure 8-1. Tempe Questionnaire

The Tempe sample was distributed in the same manner as the Glendale sample with the only exception being that the number of plates recorded was evenly distributed between two rather than four intersections.

The license plates were recorded on a typical week day during the time the lagging operation was being tested at these intersections. Each list was searched to eliminate duplicate entries. The Arizona Department of Transportation Motor Vehicle Division then generated two mailing lists of registered vehicle owners for the two samples. Two lists containing approximately 2250 names each were generated from the original two lists of 2400 license plates. The questionnaires were mailed during the time the combination leading and lagging operation was being tested.

ANALYSIS

There were 802 responses received from the Glendale questionnaire mailing. This represents a return rate of approximately 36%. Approximately 100 questionnaires were not deliverable due to incorrect addresses, change of addresses, and similar situations. The results for the Glendale questionnaire are presented in Table 8-1. A 95% confidence interval was calculated, treating each possible response as a binomial parameter. The data indicates a relatively even distribution in the frequency respondents drive in the study area. The data also indicates a high level of recognition of the changes which had occurred to the left arrow operations over the course of the study, with over 85% noticing the change in left turn arrows. Approximately 38% of the Glendale motorists responding indicated they encountered more green lights with the all leading left turn operation. This compares to approximately 16% for the all lagging operation and 24% for the combination leading and lagging operation. Approximately 17% indicated there was no difference in the three types of operations studied. With respect to left turns, approximately 49% indicated the signals are better with leading left arrows, while approximately 42% preferred the lagging operation.

There were 633 responses received from the Tempe questionnaire mailing. This represents a return rate of approximately 28%. Approximately 90 questionnaires were not deliverable. The results for the Tempe questionnaire are presented in Table 8-2. A 95% confidence interval was also calculated. The Tempe data also indicates a relatively even distribution in the frequency respondents drive in the area and a high level of recognition of the changes which had taken place. Approximately 30% of the Tempe motorists responding indicated they encountered more green lights with the all leading operation. This compares to approximately 21% for the all lagging operation and 27% for the combination leading and lagging operation. Again, approximately 17% indicated no difference. With respect to left turns, approximately 30% expressed a preference for the leading operation and approximately 61% preferred the lagging operation.

The two surveys taken together represents a composite of 1435 motorists responses. A composite of the Glendale and Tempe questionnaires is presented in Table 8-3. Nearly twice as many motorists believe they encountered more green lights with the all leading operation as compared to the all lagging operation (34.4% versus 18.3%). However, 25.3% reported they encountered the best progression with the combination leading and lagging operation. With respect to left turns, the composite results indicate a slight motorist preference for the lagging left arrow operation. Approximately 50% expressed a preference for lagging and approximately 41% prefer the leading operation. Approximately 9% expressed no preference.

Table 8-1. Public Awareness and Perception, City of Glendale

Question	Count	Percent	95% Conf. Interval
How many times per week do you drive in this area?			
0-5	218	27.2%	3.1%
6-10	212	26.4%	3.1%
11-15	150	18.7%	2.7%
16+	217	27.1%	3.1%
No response	5	0.6%	0.5%
Had you noticed this change in left turn arrows?			
Yes	691	86.2%	2.4%
No	111	13.8%	2.4%
No response	0	0.0%	0.0%
Please think about your past and present travel in this area.			
When driving in this area, do you encounter:			
More green lights with all leading left turn arrows	306	38.2%	3.4%
More green lights with all lagging left turn arrows	127	15.8%	2.5%
More green lights with some leading and some lagging	193	24.1%	3.0%
No difference	138	17.2%	2.6%
No response	38	4.7%	1.5%
With respect to left turns, are the signals:			
Better with leading left turn arrows	396	49.4%	3.5%
Better with lagging left turn arrows	333	41.5%	3.4%
No difference	73	9.1%	2.0%
No response	0	0.0%	0.0%
<hr/>			
Questionnaires Mailed:	2250		
Number of Responses:	802	36%	

Table 8-2. Public Awareness and Perception, City of Tempe

Question	Count	Percent	95 % Conf. Interval
How many times per week do you drive in this area?			
0-5	160	25.3%	3.4%
6-10	189	29.9%	3.6%
11-15	121	19.1%	3.1%
16+	156	24.6%	3.4%
No response	7	1.1%	0.8%
Had you noticed this change in left turn arrows?			
Yes	513	81.0%	3.1%
No	102	16.1%	2.9%
No response	18	2.8%	1.3%
Please think about your past and present travel in this area.			
When driving in this area, do you encounter:			
More green lights with all leading left turn arrows	187	29.5%	3.6%
More green lights with all lagging left turn arrows	135	21.3%	3.2%
More green lights with some leading and some lagging	170	26.9%	3.5%
No difference	106	16.7%	2.9%
No response	35	5.5%	1.8%
With respect to left turns, are the signals:			
Leading			
Better with leading left turn arrows	187	29.5%	3.6%
Better with lagging left turn arrows	383	60.5%	3.8%
No difference	54	8.5%	2.2%
No response	9	1.4%	0.9%
Questionnaires Mailed:	2250		
Number of Responses:	633	28%	

Table 8-3. Public Awareness and Perception, Composite

Question	Count	Percent	95 % Conf. Interval
How many times per week do you drive in this area?			
0-5	378	26.3%	2.3%
6-10	401	27.9%	2.3%
11-15	271	18.9%	2.0%
16+	373	26.0%	2.3%
No response	12	0.8%	0.5%
Had you noticed this change in left turn arrows?			
Yes	1204	83.9%	1.9%
No	213	14.8%	1.8%
No response	18	1.3%	0.6%
Please think about your past and present travel in this area.			
When driving in this area, do you encounter:			
More green lights with all leading left turn arrows	493	34.4%	2.5%
More green lights with all lagging left turn arrows	262	18.3%	2.0%
More green lights with some leading and some lagging	363	25.3%	2.2%
No difference	244	17.0%	1.9%
No response	73	5.1%	1.1%
With respect to left turns, are the signals:			
Leading			
Better with leading left turn arrows	583	40.6%	2.5%
Better with lagging left turn arrows	716	49.9%	2.6%
No difference	127	8.9%	1.5%
No response	9	0.6%	0.4%
<hr/>			
Questionnaires Mailed:	4500		
Number of Responses:	1435	32%	

DISCUSSION OF RESULTS

The results of the Glendale and Tempe surveys indicate that the largest proportion of motorists feel they encountered more green lights with the all leading left arrow operation. The composite results indicate 34.4% of the motorists responding believe they encounter more green lights with the all leading operation. This would tend to indicate that a greater number of motorists perceive traffic flow is better with the all leading left arrow operation. The two surveys are also consistent with regard to the perception of the relative merits of a combination leading and lagging left arrow operation. Both surveys indicate a greater number of motorists encountered more green lights with the combination phasing than with the all lagging operation.

The two surveys are not consistent with regard to motorist preference of leading or lagging left arrows. The Glendale survey indicates that, with respect to left turns, the leading left arrow sequence is favored. However, Tempe motorists expressed a preference for the lagging operation. One possible reason Tempe motorists may prefer the lagging left arrow operation is the proximity of the City of Scottsdale and the City of Tempe. The City of Scottsdale implemented lagging left arrows on a city-wide basis in early 1989. City of Tempe motorists are much more likely to drive the streets of Scottsdale than are City of Glendale motorists. Therefore, City of Tempe motorists were in a better position to adjust to the conversion to a lagging operation. A number of City of Tempe motorists included references to the City of Scottsdale in their comments.

The comments were generally instructive. A common theme for those who preferred the leading left arrow operation was consistency and driver expectancy. Lane blockage due to queued left turn vehicles was also a comment commonly made by those who expressed a preference for the leading operation. Safety was a reason given by both those who preferred leading and those who preferred the lagging operation. Some people simply commented on the need for left turn arrow phasing in general.

Finally, it should be noted that this sampling technique does not guarantee an unbiased sample of motorists in the Cities of Glendale and Tempe. The fact that the survey required the respondents to take the initiative to fill out and mail the questionnaire introduces some bias to the sample. But it does provide some indication of the sentiments of those people who feel as though the issue is important enough for them to take the time to fill out the questionnaire and return it. There is no reason to believe this group of people would be more inclined than the public at large to favor a leading or lagging left arrow operation. Therefore, it is felt that this sample does fairly represent the sentiments of motorists in the Cities of Glendale and Tempe.

PART V

CONCLUSIONS

PART V presents the results and conclusions of the research project.

CHAPTER 9 presents the results of the four research questions identified at the initiation of the project. It was found that intersection delay is significantly greater with lagging left turn operation. No significant change in total delay was found with third car actuation of leading protected left turn operation. No significant difference in progression was found between leading, lagging and mixed operation. No significant difference was found in accident experience between leading and lagging operation. There was a mixed response from the motorist preference survey. Glendale drivers felt left turns were better with leading while Tempe drivers felt it was better with lagging.

CHAPTER 10 presents some observations made by the research team during the conduct of the study.

CHAPTER 11 identifies future work which would be of value in this research area.

CHAPTER 9

STUDY RESULTS

In response to the five research questions stated in Chapter 1, the results of the study are as follows:

1. *Is there a difference in intersection delay at isolated intersections between leading and lagging operation?*

The results of this study indicate significantly greater delay per approach vehicle occurs with lagging operation than with leading operation for the intersections and time periods tested. The Phoenix area studies reflected a 42% increase in delay conversion per approach vehicle with conversion from leading to lagging operation. The same conversion in Pima County resulted in a 30% increase in delay per approach vehicle. It is important to note that the time periods tested were generally PM peak hour conditions. These would not be as likely to have sufficiently low left turn and through volumes to eliminate many protected left turn phases in their lagging condition. It is conceivable that in off peak conditions more of the left turns could be made in a permissive manner therefore skipping the protected left turn phase. Eliminating the protected phases would likely reduce intersection delay.

Intersection delay was also collected for test intersections with both first car and third car actuation. Although there was no significant difference between the two, this test also was only done in the PM peak hour condition. The probable benefit of third car actuation on intersection delay is most likely in off peak conditions.

2. *Is there a difference in signal progression among leading only, lagging only and mixed operation?*

There were no statistically significant differences in stops, delay or travel time with the different operating conditions. Additionally, the large number of signal timing optimization runs required to evaluate all combinations of leading and lagging operation makes for a cumbersome, time consuming process. The requirement that the Glendale and Tempe "mixed" operation was limited to either both leading or both lagging on the same street in order to avoid the "trap" restricted potential progression benefit. An additional limitation was that only four of eight multi-phase Glendale intersections and two of four multi-phase Tempe intersections were considered for change to lagging.

The most promise for benefit from lagging or mixed operation was found in the Mesa study where leading left turn operation was utilized for eastbound traffic and lagging for westbound traffic in the after condition. This was the operation which provided the best east-west progression. This mixed operation was possible without the trap condition because of the use of protected only left turns.

3. *Is there a need to have consistent left turn phasing (leading or lagging) within any given city, urbanized area and throughout the State of Arizona?*

No evidence was found in this study supporting the need to have the same phasing consistency. Although many of the cities prefer consistency within their jurisdiction, a straw poll of the representatives on the Advisory Committee found unanimous agreement that the state should not pass legislation mandating either operation everywhere.

4. *Is there a difference in accident experience between leading and lagging operation?*

In all three accident studies - Tucson, Pima County and Scottsdale, there was no significant difference in left turn accident history between leading and lagging operation.

5. *Is there a motorist preference between leading and lagging operation?*

Table 9-1 presents a summary of the information obtained in the motorists' survey. Lagging left turns seem to be more favorably received in Tempe than in Glendale. This could possibly be due to the close proximity of Tempe to Scottsdale, where lagging left turns are utilized.

Table 9-1. Public Perception Results, Phoenix Area

Question	City	
More Green Lights With:	Glendale	Tempe
Leading	38%	30%
Lagging	16%	21%
Combination	24%	27%
No Difference / No Response	22%	22%
Left Turns Better With:		
Leading	49%	30%
Lagging	42%	61%
No Difference / No Response	9%	10%

CHAPTER 10

THEORETICAL ANALYSIS OF LEADING AND LAGGING LEFT TURNS

INTRODUCTION

As a result of this study, an increased knowledge of the subtle aspects of leading verses lagging left turns was gained both by the research team and the Advisory Committee. Many of the observations made were not supported by statistical analysis due to limited sample sizes or other factors; however, it was believed to be important to try to identify some of the issues related to the question of leading and lagging left turns. This chapter is intended to serve that purpose.

The value of the field data collection and the analyses of that data can be emphasized by the fact that it provided insight to the understanding of the many variables which influence left turn operations. Within the scope of this study and the conditions at the study sites, it was not possible to collect data for all possible combinations of the pertinent variables. The results of the field studies together with a somewhat theoretical analysis yield a comprehensive assessment of leading and lagging left turn operations. This section identifies a number of variables that have an impact on the effectiveness of left turn alternatives.

The variables that should be evaluated when considering leading or lagging left turn operations are generally associated with the signal system, traffic characteristics, as well as the driver. The effectiveness of the application of leading or lagging left turns then becomes a function of the conditions at a specific intersection or location.

Table 10-1 presents a general summary of the variables that should be considered in comparing leading and lagging left turn operations. The variables listed in Table 10-1 are related to operational aspects of the problem area. It must be recognized that safety impact is the result of the decisions

Table 10-1. Decision Variables for Comparing Leading and Lagging Left Turn Operations

Signal Control
Application of actuated control
Fixed versus variable cycle length
Left-turn operations
Use of phase overlap
Network Considerations
Offset requirements
Allocation of unused green time
Traffic Characteristics
Approach volumes
Directional distribution of opposing flows
Acceptable gaps in opposing flows
Peak versus off peak volume variations
Driver Perception
Need for uniformity
Driver compliance and acceptance

related to many of the variables. For this reason, safety was not included in the list. The discussion that follows provides a more detailed explanation of the variables.

SIGNAL CONTROL

The variables associated with signal control focus on the traffic signal operation at a specific intersection. Generally, these variables are related to use of green time or have an impact on the application and allocation of green time. Included in this category are:

- application of actuated control,
- fixed versus variable cycle length,
- left turn operation,
- use of phase overlaps, and
- lost time.

This discussion assumes that exclusive left turn signals are operated on an actuated basis; thus the issue is whether the through and right turn movements are also operated on actuated control. If the intersection operates with full actuated control, there is the opportunity for the skipping of phases and the adjustment of green time in relation to the traffic demand. These factors will ultimately affect the effectiveness of the left turn operations.

Obviously, full actuated control results in a variable cycle length unless a background cycle is utilized; thus the advantage is that the signal will operate in response to the demand with the potential of reducing wasted green time. As a result, inefficiencies in left turn operations can potentially be offset by efficiencies from the actuated control. With the fixed cycle length, the need and duration of the left turn arrow can have a different result.

The left turn operation variable reflects the specific operation of left turn movements. In essence, the issue is whether left turns occur a) only in a protected phase or b) on a permitted basis in conjunction with a protected phase. One of the noted advantages of the lagging left turn is that the left turn demand may be satisfied by permitted movements; thus the need or duration of the protected movement is reduced. This advantage would not be available for the protected only operation.

One of the major advantages of the leading left turn operation is associated with the use of phase overlaps. In essence, once the minor left turn movement is satisfied, the through traffic on the approach of the heavier left turn movement is released. Given differences in opposing directional flows, the phase overlap can increase the efficiency of the signal operation. There is concern about the "left turn trap" that is created with the application of phase overlaps with lagging left turns. For this reason, jurisdictions frequently operate lagging left turns simultaneously without a phase overlap. Some work is currently being done with signal displays which will potentially eliminate the left turn trap problem. Nevertheless, the use of phase overlaps is a major consideration in terms of signal operation.

One of the elements in the analysis of intersection capacity is lost time. Basically, this is the time during a cycle that is lost due to start up delay or clearance time. Generally, the total lost time in a cycle is a function of the signal phasing. With the leading left turns and phase overlaps, there is less

lost time during a cycle than with simultaneous lagging left turns. With the lagging left turn operation, there are more situations that require the stopping and restart of traffic streams.

NETWORK CONSIDERATIONS

The variables associated with network considerations reflect signal coordination concerns. In this group, the variables are:

- offset requirements, and
- the allocation of unused green time.

In the coordination of signal networks, one of the concerns is the offset, or the time difference between the beginning of the green phase at successive intersections. Because of this concern, the issue in the application of the exclusive phase is related to the release of the through traffic at a given intersection. With the leading left turn, the through movement will be released early if the left turn phase is not fully utilized. This means that the through traffic will arrive early at the next intersection; thus the progression is affected.

It has been argued that with the lagging left turn, the duration of the left turn phase does not influence the start of the green phase. In theory, this should resolve the problem of controlling the offset; thus the lagging left turn offers an advantage.

For some network configurations, it is possible that a mixed operation of leading and lagging left turns may provide improved network coordination. The mixed operation could use leading left turns in one direction and lagging left turns in the other or simply mix the use of leading and lagging left turns depending on the offset requirement.

A factor that complicates the signal coordination problem is the allocation of unused left turn green time. If the left turn phase is not fully utilized, then the unused time for that phase must be allocated to some other phase if a fixed cycle length is maintained. With the leading left turn, the through traffic is generally released early; thus the offset with the next intersection is affected.

The allocation of unused green time with the lagging left turn will vary depending on the operation of the signal by a jurisdiction. Some jurisdictions will add the unused left turn time to the beginning of the next phase. In essence, unused left turn time on the main street will be added to the beginning of the side street through movement. Also, the unused side street time will be added to the beginning of the main street through green phase. Other jurisdictions may accumulate all unused time and add it to the beginning of the main street through movement. In either case, it results in the possible early release of the through movement which disrupts the planned offset.

Basically, both types of left turn operations have a potential adverse impact with respect to the planned offset. For a given location, it is necessary to evaluate the probability of having unused green time and the effect on network operations.

TRAFFIC CHARACTERISTICS

Whether the intersection signals utilize left turn actuations only or include actuated control for some or all through movements, there are a number of traffic variables that can influence the left turn operations. These variables include:

- approach volumes,
- directional distribution of opposing flows,
- acceptable gaps in opposing flows, and
- peak versus off peak volume variations.

The approach volumes reflect the general magnitude of the traffic movements as well as the percentage of left turns at a given intersection approach. Basically, the magnitude of the approach volumes will have an impact on the need for the protected left turn movement. As the volumes increase at an intersection, it is less likely that the left turn demand can be accommodated by the permitted operation. For this reason, the probability that the lagging left turn phase will not be needed decreases. In addition, increases in volumes will potentially increase the probability that the left turn phase will be fully utilized.

The directional distribution of the opposing flows affects the possibility of phase overlap operation as well as the advantage of the phase overlap accommodating the through movements. With balanced left turn and through movement approach volumes, the advantage of the phase overlap with the leading left turn operation is eliminated. With the elimination of phase overlap operation, the efficiency for the leading operation is similar to the lagging operation.

The number of acceptable gaps in traffic opposing a permitted left turn movement will influence the permitted left turn capacity. For both a protected/permissive and a permissive/protected operation, the larger the permitted left turn capacity, the less time which must be dedicated to the protected left turn phase. A large left turn volume coupled with a large permitted left turn capacity may overcome some of the disadvantages associated with a lagging operation under the conditions of high directionality. With a lagging operation, the permitted left turn capacity is first fully utilized then the protected phase is used to satisfy the residual left turns. The opposite is true for a leading operation, where the capacity of the protected phase is first exhausted. An accurate evaluation of the permitted left turn capacity is much more critical to the efficient timing of the lagging left arrow operation.

Typically, traffic engineers are concerned with the peak conditions; however the off peak traffic volumes may yield a different set of results in terms of demands on signal operations. For example, the left turn demand in the off peak periods could possibly be satisfied without the need for protected turn phases. With this condition, there would be a potential advantage to the lagging left turn operation due to the fact that the left turn phase would only be used if needed. Similarly, third car actuation could result in more delay reduction in the off peak periods, than in the peak periods. Thus, it is possible that the operation of the intersection could be improved. One of the factors to be considered, therefore, is the difference in peak and off peak traffic conditions. Although traffic engineers are typically concerned with the peak conditions, they should be just as concerned with what happens during the other 22 hours of the day.

DRIVER PERCEPTION

An important element in the operation of any signal system is the perception of the driver. Variables related to driver perception are:

- the need for uniformity, and
- driver compliance and acceptance.

One of the basic considerations for the application of traffic control devices is uniformity. Certainly, there are arguments that leading and lagging left turn operations should not be mixed because of the lack of uniformity. On the other hand, some mixed operations even in Arizona apparently go unnoticed by the motoring public. If the driving population perceives the need for uniform left turn operations, then the effectiveness of mixing the operations will potentially be affected. The true question to be resolved is the importance of uniformity for a particular area.

While not totally unrelated to the uniformity issue, another driver variable is compliance and acceptance. For example, if the drivers comply with the signal display, uniformity may not be as great an issue. Anticipation on the part of the driver, as a result of uniformity, can be dangerous as well. Certainly, it is likely that differing driver populations may yield differing responses in terms of compliance and acceptance.

CHAPTER 11

RECOMMENDATIONS FOR FUTURE WORK

Through the conduct of this study, several questions have arisen which are outside the scope of this project. These are identified here as possible items for future research.

- *Effectiveness of lagging* left turns and third-car actuation in off-peak conditions. The studies of lagging and third car operation conducted in this project were primarily during the PM peak periods. A major potential benefit of both lagging left turns and third car actuation lies in the possibility of eliminating protected left turn phases. In a lagging operation, if the left turns can be accommodated on the permissive green thereby eliminating the protected phase, a reduction in intersection delay should result. Similarly, if fewer than three cars arrive prior to the beginning of a protected left turn phase, delay should be reduced with third car actuation. For this reason evaluation of off-peak delay comparing leading with lagging left turns and third car actuation with first car actuation would be valuable.
- *Effectiveness of leading* left turns in one direction and lagging left turns in opposing direction. As tested at one Mesa intersection, there is the potential for improvement to progression at locations where the platoons arrive at different times to have the left turns lead in the direction the platoon first arrives and lag in the opposing direction. The sample size in this research project was inadequate to make a conclusive statement, however, the Mesa results were very promising.
- *Feasibility of overcoming "trap"* but allowing combination of permissive leading or lagging with phase overlap. Current experimentation in Texas is evaluating the use of a 5 section programmed visibility head (Dallas signal face display) for left turn drivers. This head would continue to display a circular green indication to left turn drivers whose concurrent through movement is terminated but whose opposing through movement continues. Although this method has good results (14) the signal display violates section 4B-12 (3.2.) (15, p.4B-12), of the MUTCD which states:
 2. *During the permitted left turn movement, all signal indications on the approach shall display all a.c. CIRCULAR GREEN indication.*

A formal request has been made by the Texas State Department of Highways and Public Transportation to revise the MUTCD to allow the Dallas signal face display. Appendix G shows the typical phasing and special (Dallas) phasing being tested.

- *Signal optimization software* which evaluates options of combinations of leading and lagging left turns and which predicts protected lagging phase duration based on permissive left turn phase capacity. Although PASSER II will evaluate the combination of leading and lagging left turns on arterial streets, the research team is unaware of software which will accomplish this for a grid. In this research project the FORCAST optimization software developed by Computran Systems, Inc. was used with all possible combinations of leading and lagging left turns within the constraints of either both leading or both lagging on the two approaches of the same street. In the lagging situation however, FORCAST does not consider the

permissive left turns which can be made during the through movements, therefore it overestimates the green time required for the protected lagging phase. This results in a higher cost prediction than actually would result. It is impossible therefore to determine the true lowest cost phase combination. A software program should be developed which:

- Evaluates all possible combinations of leading and lagging left turns for a grid, and,
- Includes a gap acceptance algorithm which will predict the number of left turns which can be made during a permissive period and the resulting required protected lagging phase durations.
- *Evaluation of "trade off" of uniformity* verses the benefit of varying left turns between leading and lagging under different conditions. There is a perceived value of having a uniform left turn treatment. It is unlikely that this could or should be made completely uniform throughout the country, state or even an individual city. On the other hand, it is logical that the greatest efficiency of system operation (i.e. least delay) would come from the ability of varying between leading and lagging left turns not only from intersection to intersection, but also from approach to approach at a given intersection. The optimum performance likely would result from analyzing all combinations of leading and lagging left turns at each approach for each time period evaluated. In this case, an approach might be leading in one period of the day and lagging in another. Figure 11-1 graphically portrays this trade off. This analysis would necessitate evaluating a very large number of combinations of phase options. It may be desirable to develop software which would perform a two step optimization process.
- Coarse level analysis to determine best combination of leading and lagging left turn phase, and
- A more detailed analysis similar to TRANSYT 7F

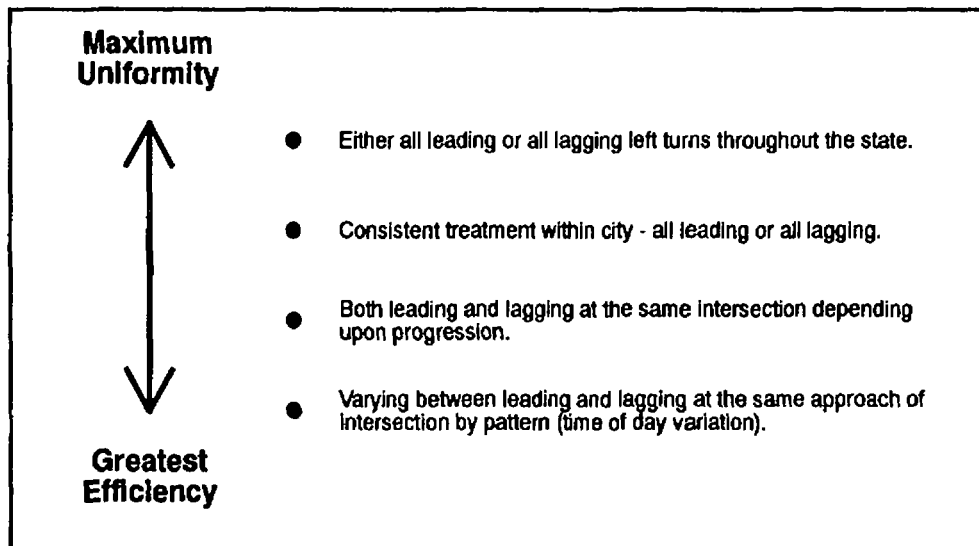


Figure 11-1. Hierarchy of Left Turn Uniformity

- *Additional work* would include an evaluation of driver expectancy of left turns vary between leading and lagging by time of day. As stated previously, it is expected that a reduction in delay should result from considering all possible combinations of phasing for each time period being optimized. A study should be made of possible driver confusion resulting from such a treatment.

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